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LM02 Mirror Magnet Test Summary

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Content:

1. Introduction

LM02 is the first 4-m long Nb_3Sn dipole coil assembled and tested in a "mirror" configuration at Fermilab as part of the new generation high-field accelerator magnet technology scale-up program. One of the two coils in this "mirror" magnet was replaced with a half-cylinder made of low carbon steel. The LM02 coil was made of 27-strand Rutherford cable with advanced 1-mm Nb_3Sn RRP-108/127 strands (i.e. with increased number of sub-elements). Total length of the cable in the magnet is ~166 m.

The magnet was installed into the VMTF dewar and it was electrically checked by November 16th, 2007. The VMTF dewar was filled with liquid helium on November 19th. First thermal cycle (TC-1) was started on November 19 and was completed on December 12, 2007. The second thermal cycle (TC-2) was started on January 4th and was finished on January 12th, 2008. Both TC-1 and TC-2 included quench training and ramp rate dependence study at 4.5 K and 2.1 K. Finally the LM02 magnet has been removed from the VMTF dewar on January 22, 2008.

The Voltage Spike Detection System (VSDS) was used for detection of small magnetic flux changes in the magnet. Results of the LM02 spike data analyses, as well as of the magnet mechanical analyses, will be presented in a separate note.

2. Quench History

The magnet test program started with quench training at 20 A/s ramp rate at 4.5 K temperature. The quench detection threshold for the Half-coil signal was set to 500 mV at the beginning of test (the Half-coil signal for this magnet is "inner minus outer" layer signals). The magnet has been equipped with two strip heaters located on the outer surface of the outer layer, as shown in Fig.7 (top left). They were connected to the different heater fire units (HFU). In the beginning both heaters were set in protection mode with heater supply voltage at 300 V and with delay 0 ms. The dump delay was set to 1 ms.

From the very beginning of test, splice voltage signals at both positive and negative leads were found to have ~200 mV of noise, while expecting few mV. We performed 0A trips to capture splice data in order to determine if the noise source was from the power system or from the external instrumentation – cabling, isolation amplifiers, or ADCs. The observed level of noise was 2-7 mV depending on whether the power supplies were switched OFF or ON respectively. These results suggest that the noise source was the power system upstream of the external cabling and instrumentation. Also, an FFT of the signals at quench revealed typical power supply harmonics: 120 Hz, 180 Hz, 240 Hz, 720 Hz, etc. A follow-up inspection of the magnet wiring after the test may clarify the reasons for this large noise in segments around the splices. The noise in splices did not impact the quench training since they were canceling each other when subtracting the half coil signals.

2.1 Test cycle 1

Full quench history is presented in Fig.1 and also in Tables 1 and 2.

Training at 4.5 K started with quenches in low field region of the outer layer (mid-plane segment) with high (16-18) MIITs. To protect conductor from overheating we reduced the half-coil quench detection threshold first to 200mV and then after quench #5 to 100 mV. Later on we increased this threshold temporarily during the ramp rate study, but the operating threshold for the quench detection system remained at 100 mV during the whole test.

Magnet performance was rather erratic. Quench current varied from ~15 kA to ~17 kA without any indication of training. Therefore we started the ramp rate study and another strange behavior was found very soon. At high ramp rates 150 A/s and higher, the magnet was quenching at 3-4 kA with quench development in mid-plane segments of both inner and outer coil layers.

Empirically it was found that "conditioning" ramps helped to reach much higher quench current at the same high ramp rates. During the "conditioning" ramp current was ramped up to ~10 kA and then down to 0 A both at the rate of 100A/s. Later on we found that quench current also is passing the 3-4 kA regions if ramp up first to 5 kA at low ramp rate and then continue ramping to quench at high ramp rates. Conditioning ramps nevertheless did not help at low ramp rates and the magnet still was quenching at the same 15-17 kA current in the outer layer.

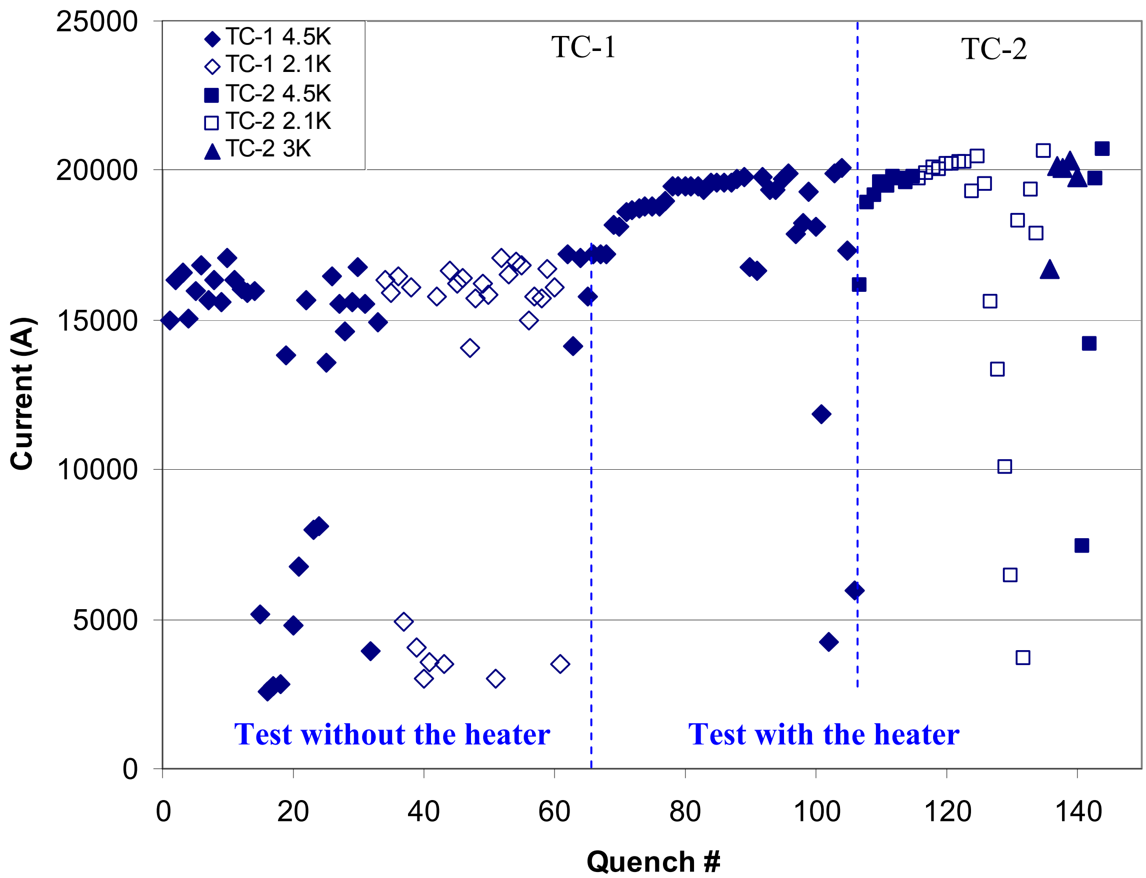


Fig.1. LM02 quench history in both 1st and 2nd thermal cycles of the test.

Quench locations shown in Fig.2 specify either outer or inner layer of the quench origin. As one can see most quenches in the first part of TC-1 occurred in outer layer, mostly in mid-plane (6ou_os30) segment. The coil drawing with the voltage tap segment locations is shown in Fig.3, the coil cross section is shown in Fig.7, top left.

After the ramp rate study at 4.5 K the magnet was cooled down to 2.1 K but the quench performance did not change much. In fact we did not notice any temperature dependence at low or high ramp rates.

Location of most of the quenches in the lowest field segment made us think that we are facing problem related to the low field instability. It was decided to warm-up one of the two strip heaters located over the outer layer mid-plane segment in order to decrease the local Jc and therefore reduce the instability in the local conductor. Comprehensive magnet simulation was performed to estimate heat transfer from the strip heater to coils and determine the required heater current. Details of the test with the heater will be summarized in next section of this report.

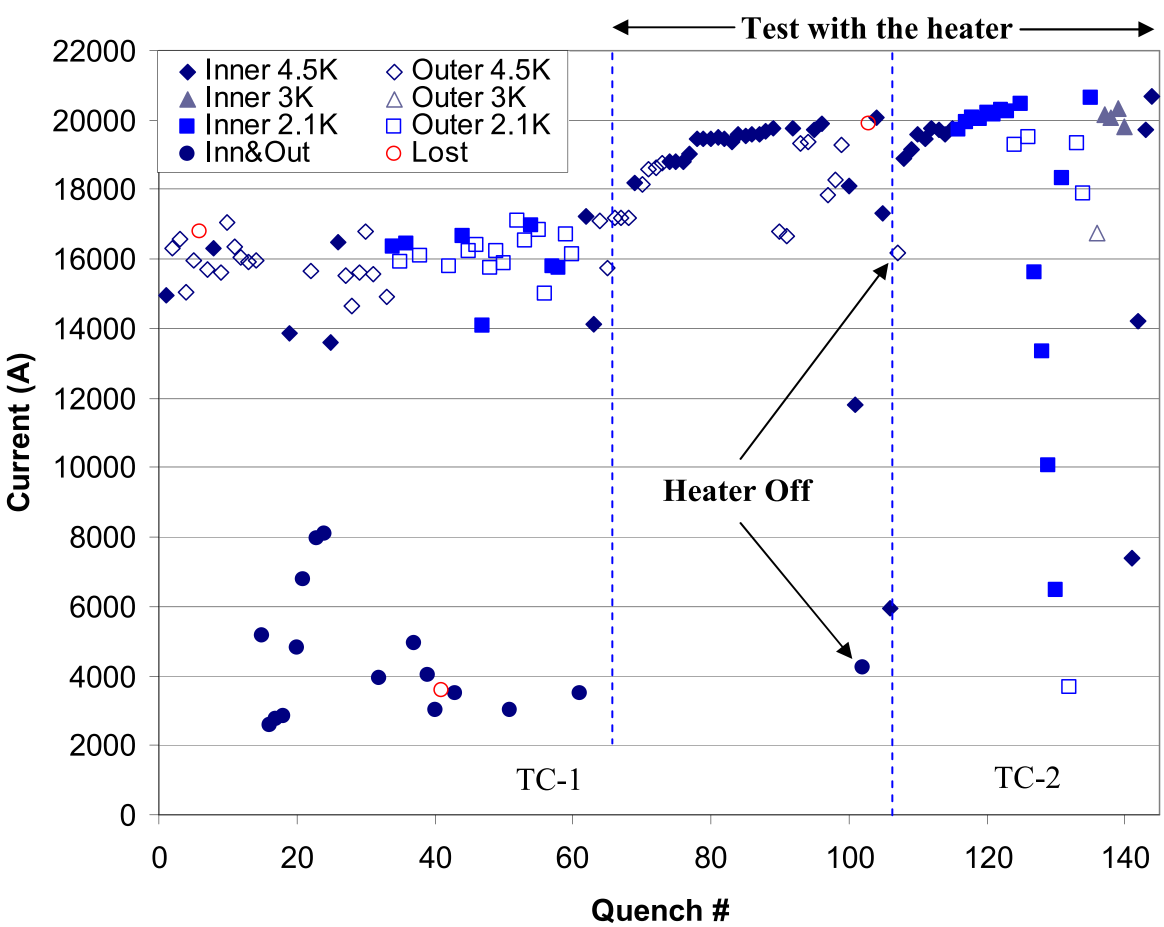


Fig.2. Location (layer) for all the LM02 quenches.

Test with the heater was started after quench #66 when the magnet was warmed up to 4.5 K again. First three quenches with the 2.02 A heater current still occurred in the outer layer, but now the magnet did not exhibit the erratic behavior and started quenching almost at the same current. Then the first training quench occurred in the innermost segments of the inner layer at the slightly increased heater current of 2.55 A. Later on it was shown that the instability in outer layer is quite sensitive to the heater current and to the amount of heat transferred from heater to the coil, i.e. to temperature of the coil.

Detailed quench locations for quenches during the test with the heater (quenches #66 and later) are shown in Fig.5. For comparison quench locations of first 65 quenches are also shown in Fig.4.

At the end of TC-1 we have demonstrated that the quench current is much higher with the heater current (i.e. with warmed-up mid-plane segment of the outer layer) than without this current. For quench #102 we switched off the heater current and magnet quenched again in outer layer at significantly lower current (see Table 1 and Fig.1).

The highest quench current in the 1st thermal cycle was ~20100A reached in the quench #104 at 5 A/s ramp rate and I_{HFU2} = 2.38 A current on the heater. With the quench #106 the thermal cycle 1 was completed and the magnet was warmed up to room temperature. Magnet was idle at room temperature in the VMTF dewar from midnight of December 20 to 9:00 pm of January 2, 2008.

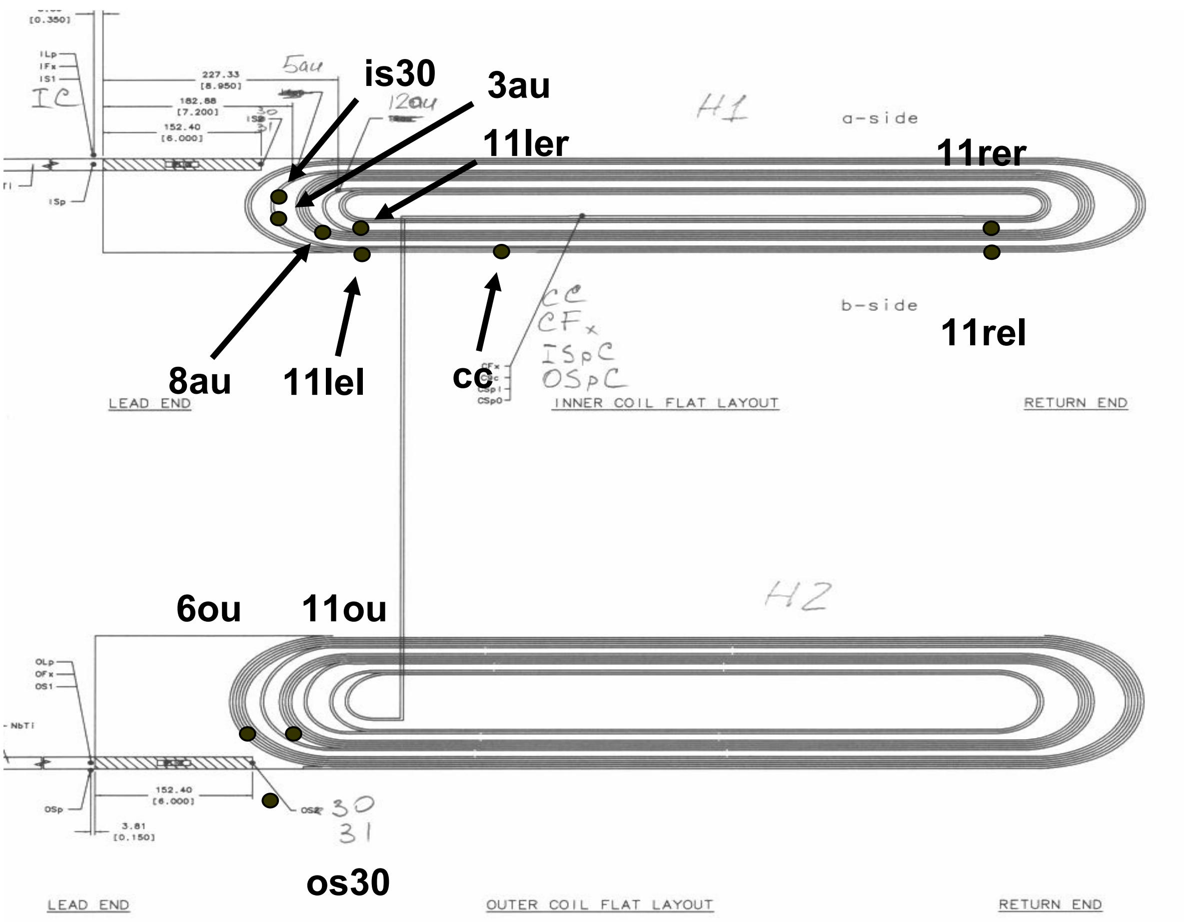


Fig.3 Coil drawing with the voltage tap segment allocation.

2.2 Test Cycle 2

Cool down in the 2nd test cycle was started on January 2nd, 2008 and cold Hipot at 4.5K was done on January 4th. At the beginning the magnet showed some training with quenches in the innermost segments on the inner layer and at quench #112 we reached the quench current of the order we had by the end of 1st thermal cycle at 4.5 K: ~19.5-19.7 kA with the strip heater at 2.38 A (first in TC-2 quench #107 was performed with strip heater at zero current).

After the quench #115 the magnet was cooled down again to 2.16 K to repeat the heater test at different temperature. First we planned to set heater at 3.2A current to pass the temperature on the outer layer mid-plane segment at about 6.4 K according to the simulation. But our *Kepco* power supply was not able to provide more than 3.05 A current due to its voltage limitation (40 V max). Fortunately the heat provided at this current was enough to avoid quenches in the outer layer.

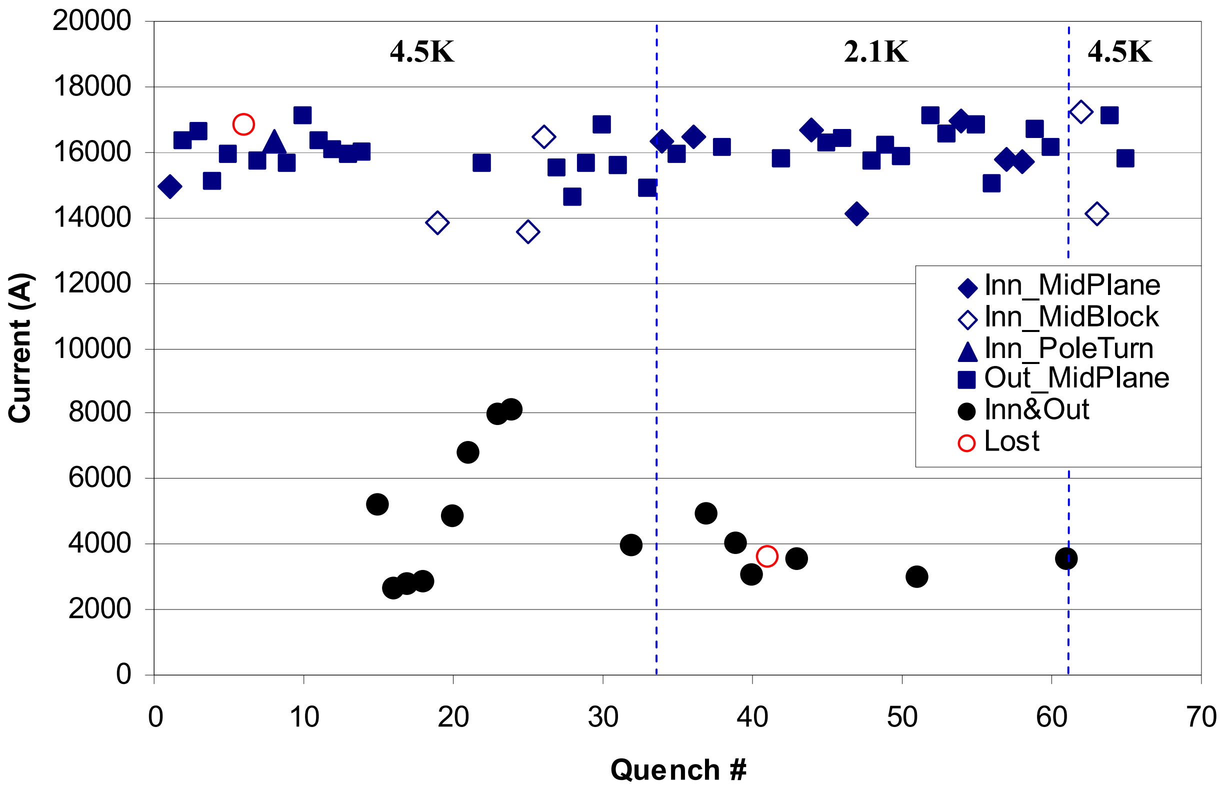


Fig.4 Detailed quench locations for quenches 1-65 without heater current.

After a couple of training quenches at 2.16 K we easily reached the quench current of 20.2-20.4 kA.

Test at 2.1 K was finished with the ramp rate study and the highest quench current ~20600 A was reached in the quench #135 at ramp rate 10 A/s. Results of the ramp rate study will be reported in Section 4.

Next we also performed 5 quenches at 3 K for the temperature dependence study. The quench program in the 2nd thermal cycle was completed at 4.5 K again with taking few more quenches at different ramp rates. The heater current was set to 2.39 A to be consistent with the ramp rate study at 4.5 K in 1st thermal cycle.

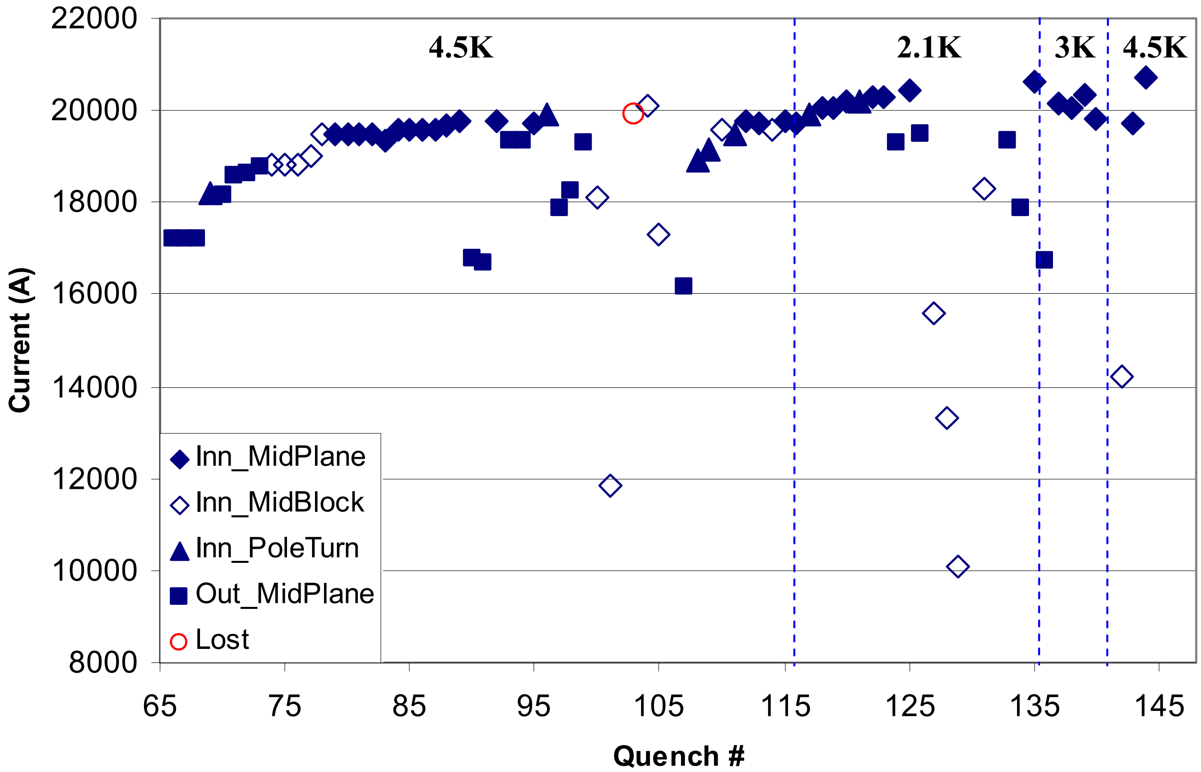


Fig.5 Detailed quench locations for the test with the strip heater (quenches 66 and later).

At the very end of TC-2 the magnet was ramped up to ~ 19 kA at the rate of 10 A/s, then the heater current was reduced from 2.39 to 0 A providing the lower temperature of the inner layer mid-plane segment. In this way we reached the highest quench current ~ 20700 A (10 A/s ramp rate) during the whole test of this magnet.

Quench multiplicity in the inner and outer layers with and without the strip heater is summarized in Fig.6. 144 quenches were performed in total and only in 8 of them quench was developed in the innermost segments of the inner layer. At the end of this report we will show the estimated quench locations for these 8 quenches.

During the test we had several low current trips detected by the Analog Quench Detection (AQD) system while the Digital Quench Detection (DQD) system did not show any activity in the half-coil signals. These quenches always occur at ~ 200 A and show sharp narrow spikes in both half-coil signals of the AQD. We think it could be related to the power supply. The reason why the DQD did not see these spikes is that different filters are used for the signal conditioning in the AQD and DQD. In the 1st thermal cycle we reduced the power supply voltage regulator gain (bandwidth setting changed from

20Hz to 5Hz) to help reduce ripple by slowing the power supply response. Nevertheless we had a few such trips in the 2nd thermal cycle too. One may speculate that we always had these spikes in the AQD half-coil signals and they were canceling each other, but for some unknown reasons sometimes this balance fails and the AQD trips. In the past we also had much higher (500-750 mV) thresholds on the Half-coil signal.

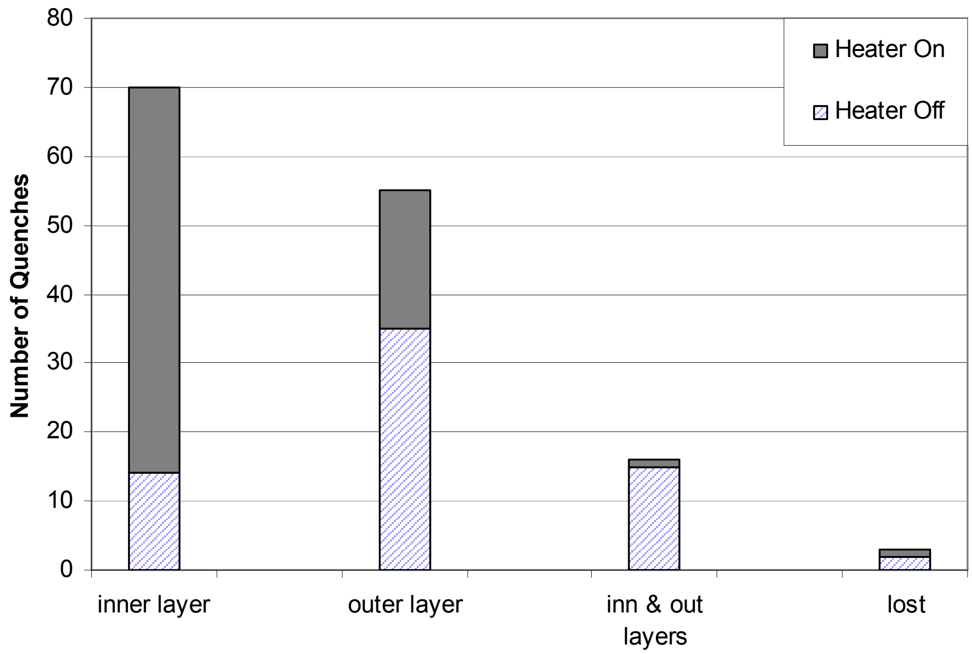


Fig.6 Quench multiplicity in the inner and outer layers with and without current on the strip heater.

We lost data for quenches 6, 41 and 103. No particular reasons were found for these failures (*Pentek* data loggers have always had VME bus error problems at a low level) and as a preventive measure we should replace the CPU used in the VMTF data logger with an up-to-date model.

Table 1: LM02 Quench History with comments

File	#	Current (A)	I (HFU) (A)	dI/dt (A/sec)	t_{quench}	MIITs	Mag Temp Bot (K)	Mag Temp Top (K)	Comments [notes in brackets were added later]
Test Cycle I									
lm02.Quench.071119130323.653	**-**	5005		100	-0.162	5.62	4.43	4.43	fired heater HFU2 @300V, induced quench at 5000A after balancing completed. Studying signals...
lm02.Quench.071119142541.269	**-**	5005		100	-0.155	5.37	4.43	4.42	we fixed missing strip heater taps (cable disconnected) and redundant taps for new isoamp checkout (wrong channels). Fired heater HFU1@300V, 5kA, to check signals again dump delayed 25ms
lm02.Quench.071119145855.028	**1**	14971		20	-0.021	10.02	4.44	4.44	first 4.5K training ramp at 20A/s to quench just under 15kA.
lm02.Quench.071119153259.338	**-**	5280		20	-0.056	2.57	4.43	4.43	Investigating. [it was a ground fault trip]
lm02.Quench.071119163859.701	**2**	16322		20	-0.041	16.86	4.43	4.44	3rd ramp, 2nd quench at 20A/s, 4.5K
lm02.Quench.071119171751.104	**3**	16599		20	-0.044	18.33	4.44	4.44	this time the VSDS current signal was connected. (20mV threshold on VSDS Hcoils) third training quench at 4.5K, 4th ramp.
lm02.Quench.071119181756.420	**4**	15074		20	-0.042	14.92	4.43	4.43	dqd_coil detected quench at just over 15kA... we will have to check whether this is real (vs due to a flux jump)
lm02.Quench.071119185103.187	**5**	15961		20	-0.042	16.66	4.43	4.43	half coil thresholds still 0.2V to keep MIITS down. 6th 20A/s ramp, 5th training quench at 4.5K
lm02.Quench.071119192825.509	**6**	16826		20	-0.007	8.04	4.43	4.44	quench at 16809A, T=4.42K, ramp rate 20A/s [part of the data was lost]
lm02.Quench.071120095152.786	**-**	2286		?	-0.549	3.43	4.42	4.43	power system tripped at 2kA [too high ramp rate when testing PS]
lm02.Quench.071120103537.292	**7**	15703		20	-0.034	14.07	4.44	4.44	quench at 15691.5A, 20A/s, 4.42K.
lm02.Quench.071120112938.135	**8**	16340		20	-0.004	6.75	4.43	4.44	quench at 16327A, 20A/s, 4.42K
lm02.Quench.071120122407.002	**9**	15641		20	-0.022	10.95	4.43	4.44	DQD coil detected quench at 15629.2A, 4.42K, 20A/s

lm02.Quench.071120131733.411	**10**	17083		20	-0.011	9.43	4.43	4.44	dqd-coil detected quench at 17067.2A, 4.42K, 20A/s
lm02.Quench.071120150123.608	**11**	16376		20	-0.020	11.36	4.44	4.44	quench at 16363.4A, 20A/s, 4.42K
lm02.Quench.071120154432.849	**12**	16067		20	-0.033	14.40	4.44	4.44	dqd half coil threshold was raised to 0.2V - VSDS shows that we may be seeing large, fast voltage spikes, which could integrate to cross threshold... we crossed dqd half coil threshold at 16057A.
lm02.Quench.071120163503.638	**13**	15928		20	-0.040	15.84	4.44	4.44	dqd half coil threshold was lowered again to 0.1V.
lm02.Quench.071120170718.983	**14**	15995		20	-0.024	11.94	4.43	4.44	4.5K 20 A/s
lm02.Quench.071120180456.296	**15**	5171		300	-0.026	1.67	4.42	4.42	200 [note added later - this ramp was nominally 300 A/sec]
lm02.Quench.071120185422.368	**16**	2448		250	-0.603	4.12	4.42	4.42	quench at 2500A, ramp rate 250A/s, 4.42K.
lm02.Quench.071120193128.628	**17**	2631		250	-0.434	3.43	4.42	4.42	quench at 2738A, ramp rate 250A/s, 4.42K.
lm02.Quench.071120194619.494	**18**	2754		200	-0.357	3.10	4.42	4.42	quench at 2824A, ramp rate 200A/s, 4.42K
lm02.Quench.071120201402.612	**19**	13863		200	-0.006	5.90	4.43	4.43	we started with ramp rate 100A/s and get above 10kA, so we have decided since AQD and DQD threshold is 500mV it's better to ramp down and immediately start ramp up at 150A/s. But at this ramp rate we reached current above 10kA and ramped down again. Finally, at ramp rate 200A/s we quenched at ~13kA.
lm02.Quench.071120203347.678	**20**	4773		150	-0.312	8.04	4.42	4.42	quench at 4817.4A at ramp rate 150A/s.
lm02.Quench.071120204915.176	**21**	6781		300	-0.014	19.66	4.43	4.43	we don't understand clearly what happened - w/o quench detection the slow ramp down started and in 250ms dump was fired. [see Section 6]
lm02.Quench.071121114634.526	**-**	1004		20	0.011	0.70	4.42	4.42	testing the system at 1000A.
lm02.Quench.071121122741.214	**22**	15663		20	-0.046	17.07	4.43	4.44	we ramped up to 9kA with ramp rate 100A/s and then till quench at 20A/s. quench at 15654A, 4.42K
lm02.Quench.071121150510.382	**23**	7973		300	-0.014	2.92	4.43	4.43	we made 2 conditioning ramps upto 10kA at rates 100A/s and 150A/s and then ramped to quench at 300A/s. 4.42K.
lm02.Quench.071121153631.684	**24**	8075		250	-0.168	13.09	4.43	4.43	One conditioning ramp at 100A/s. quench at ~8200A at ramp rate 250A/s.
lm02.Quench.071121163004.596	**25**	13605		200	-0.003	5.19	4.43	4.43	One condit. ramp at 100A/s upto 10kA. Then ramp up to quench at 200A/s.

lm02.Quench.071121172131.773	**26**	16498		150	-0.002	6.60	4.43	4.43	One conditioning run at 100A/s upto 10kA. Quench at 16486A with ramp rate 150A/s.
lm02.Quench.071121181548.267	**27**	15536		100	-0.041	15.57	4.44	4.44	one conditioning ramp upto 10kA at 100A/s. Quench at 15528.2A with ramp rate 100A/s.
lm02.Quench.071121192932.608	**28**	14642		4	-0.040	13.77	4.44	4.44	one conditioning ramp upto 10kA @ 100A/s. Ramp to 11kA at 20A/s and then ramp to quench at 4A/s
lm02.Quench.071123091720.493	**29**	15635		50	-0.039	15.26	4.45	4.45	quench at 15612.4A, ramp rate 50A/s, 4.43K. One conditioning ramp upto 8kA at 50A/s.
lm02.Quench.071123133325.864	**30**	16825		75	-0.013	9.80	4.45	4.45	quench at 16796.5A at ramp rate of 75A/s. 2 conditioning ramps at 100A/s and 50A/s till 10kA and 14kA respectively.
lm02.Quench.071123143419.163	**31**	15591		10	-0.039	15.10	4.45	4.45	quench at 15569A, ramp rate 10A/s, 4.43K, 2 conditioning ramps at 100A/s and 50A/s (upto 10kA and 15kA).
lm02.Quench.071123164637.194	**32**	3905		200	-0.139	2.74	4.43	4.43	quench at 3924A with ramp rate 200A/s and no conditioning ramp.
lm02.Quench.071123180710.753	**33**	14919		5	-0.030	11.99	4.45	4.45	quench at 14895.9A with ramp rate 5A/s, one conditioning ramp at 20A/s.
lm02.Quench.071124104716.201	**34**	16390		20	-0.003	6.98	2.16	2.15	First quench at 2.15K, quench current I=16361.9K, ramp rate 20A/s.
lm02.Quench.071124113231.661	**35**	15935		20	-0.024	11.98	2.16	2.15	quench at 15905.3A, ramp rate 20A/s. 2.15K.
lm02.Quench.071124122232.602	**36**	16512		20	-0.003	6.86	2.16	2.15	quench at 16458.8A, ramp rate 20A/s, 2.15K. One conditioning ramp at 100A/s was done up to 12kA.
lm02.Quench.071124132800.667	**37**	4934		150	-0.029	1.63	2.16	2.15	quench at 4926.4A with ramp rate 150A/s. No conditioning ramp, 2.15K.
lm02.Quench.071124140104.263	**38**	16139		150	-0.017	10.30	2.16	2.16	quench at 16111.2A with ramp rate 150A/s. This time one conditioning ramp was done at 100A/s upto 12kA.
lm02.Quench.071124151130.190	**39**	4035		250	-0.054	1.51	2.16	2.15	quench at 4036.7A with ramp rate 250A/s, 2.16K. One conditioning ramp with ramp rate 100A/s upto 11kA.
lm02.Quench.071124152623.690	**40**	3013		250	-0.079	1.10	2.15	2.15	This time no conditioning ramp, quench at 3027.9A with ramp rate 250A/s.
lm02.Quench.071126100235.880	**41**	3587		200	0.000	0.00	0.00	0.00	Data were lost
lm02.Quench.071126120537.599	**42**	15813		20	-0.028	12.95	2.16	2.15	Quench at 15795.6A with ramp rate 20A/s. One conditioning ramp with ramp rate 100A/s upto 12kA. 2.15K.
lm02.Quench.071126130008.144	**43**	3464		200	-0.255	3.60	2.15	2.15	quench at 3512A with ramp rate 200A/s. No conditioning ramp, 2.16K.
lm02.Quench.071126143040.829	**44**	16652		100	-0.004	7.27	2.16	2.15	quench at 16645.8A @ 100A/s. 2.16K. No conditioning ramp.

lm02.Quench.071126152519.792	**45**	16250		74	-0.022	11.86	2.16	2.16	quench at 16241.2A with ramp rate 75A/s. 2.16K, no conditioning ramp.
lm02.Quench.071126160256.532	**46**	16398		50	-0.025	12.71	2.16	2.16	quench at 16392A with ramp rate 50A/s. 2.16K. No conditioning ramp.
lm02.Quench.071126173753.954	**47**	14096		4	-0.006	6.18	2.16	2.15	quench at 14090.8A with ramp rate 5A/s. No conditioning ramp, 20A/s ramp rate upto 10kA
lm02.Quench.071126185952.423	**48**	15736		100	-0.027	12.57	2.16	2.16	quench at 15731A with ramp rate 100A/s, 2.16K. One conditioning ramp to 10kA at ramp rate 100A/s.
lm02.Quench.071127093039.799	**49**	16230		10	-0.015	9.93	2.15	2.15	quench at 16218.5A with ramp rate 10A/s. One conditioning ramp at 100A/s up to 10kA. T=2.16K.
lm02.Quench.071127103015.457	**50**	15873		175	-0.027	12.44	2.16	2.16	quench at 15870.2A with ramp rate 175A/s, at 2.16K. One conditioning ramp to 10kA at rate 100A/s.
lm02.Quench.071127104723.092	**51**	2910		300	-0.391	3.78	2.15	2.15	quench at 3003.9A with ramp rate 300A/s. No conditioning ramp.
lm02.Quench.071127120138.030	**52**	17098		20	-0.161	53.53	2.16	2.15	quench at 17087.3A with ramp rate 20A/s, 2.16K. Conditioning ramp to 2kA at ramp rate 20A/s. [no filtering capacitors on PS]
lm02.Quench.071129150553.178	**-**	198		10	-0.003	0.04	4.21	4.33	aqd detected quench at 200A, 4.2K, ramp tate 10A/s
lm02.Quench.071130115729.273	**-**	197		20	-0.007	0.07	4.43	4.42	Trip at 200A again
lm02.Quench.071203125619.345	**53**	16549		20	-0.024	12.73	2.16	2.16	after AQD/DQD check out at high current we quenched at 16535A with ramp rate 20A/s, T=2.16K.6036567
lm02.Quench.071203160128.335	**54**	16970		20	-0.003	7.21	2.17	2.16	quench at 16963.1A, 2.16K, LL=15.2. Initial ramp up to 14kA at 20A/s and then ramp down to 13kA followed with ramp to quench with ramp rate 20A/s.
lm02.Quench.071203164257.645	**55**	16842		20	-0.020	11.84	2.17	2.17	quench at 16833.5A, 2.2K. Ramp up to 14kA and then down to 12kA, followed with ramp to quench with ramp rate 20A/s.
lm02.Quench.071203175459.996	**56**	15014		0	-0.021	10.17	2.17	2.17	Ramp to 15kA with ramp rate 15A/s and stayed at plateou for 5min before it quenched. 2.17K.
lm02.Quench.071203183601.753	**57**	15789		20	-0.004	6.73	2.17	2.16	quench at 15775.9A with ramp rate 20A/s. 2.17K. (ramp up to 14kA and then ramp down to 11kA, followed with ramp to quench)
lm02.Quench.071203191758.994	**58**	15738		20	-0.003	6.55	2.17	2.17	quench at 15726.9A, ramp rate 20A/s. 2.16K. 14kA/10kA.
lm02.Quench.071204101939.213	**59**	16702		20	-0.017	11.04	2.16	2.16	20A/s, 14kA/9kA (Summaries for this and following 5 quenches were added manually)
lm02.Quench.071204112239.628	**60**	16128		20	-0.016	10.19	2.16	2.16	Ramped to 15kA and stayed at plateou for >10min, then ramp down to 8kA since didn't quench.

lm02.Quench.071204114718.483	**61**	3514		175	-0.180	3.02	2.16	2.16	quench at 3514A with ramp rate 175A/s. No conditioning ramps. 2.16K
lm02.Quench.071204164622.585	**62**	17240		150	-0.004	7.24	4.43	4.43	ramp rate 150A/s (50A/s upto 5000A). 4.43K.
lm02.Quench.071204182026.624	**63**	14158		200	-0.006	5.72	4.43	4.43	ramp rate 200A/s (50A/s upto 5000A)
lm02.Quench.071204183645.423	**64**	17097		150	-0.015	10.30	4.43	4.43	quench at 17087.7A with ramp rate 150A/s. Ramped first to 5000A at rate 50A/s and then to quench at 150A/s.
lm02.Quench.071206110830.848	**65**	15764		75	-0.021	10.95	4.45	4.45	we did regular quench at 75A/s prior to the test with heater. 4.45K.
lm02.Quench.071206160652.262	**66**	17205	2.02	75	-0.007	8.44	4.47	4.47	quench at 17194A, ramp rate 75A/s, 4.4K. HFU1 in a protection mode, HFU2: 1.88A.
lm02.Quench.071206165145.240	**67**	17200	2.02	75	-0.012	9.93	4.48	4.48	quench at 17193A, ramp rate 75A/s, 4.45K. HFU1 - prot.mode, HFU2: 1.88A.
lm02.Quench.071206171848.743	**-**	184	2.02	75	-0.004	0.04	4.48	4.48	low current trip at 200A again.
lm02.Quench.071206173247.770	**68**	17204	2.02	75	-0.013	10.37	4.48	4.49	quench at 17196.1A with ramp rate 75A/s. 4.48K. HFU1 prot.mode, HFU1: 1.85A.
lm02.Quench.071206184456.470	**69**	18199	2.55	75	-0.002	7.40	4.50	4.50	quench at 18197.8A with ramp rate 75A/s. HFU1 in a prot.mode, HFU2 - 2.41A.
lm02.Quench.071206193612.436	**70**	18131	2.55	75	-0.268	94.95	4.50	4.50	quench at 18139A with ramp rate 75A/s, 4.49K. HFU1 protection/HFU2 2.4A. [MIITs number is based on overestimated quench start time. Real start time was -0.009s]
lm02.Quench.071207114658.721	**71**	18607	2.56	75	-0.003	8.18	4.48	4.50	quench at 18595.3A with ramp rate 75A/s, 4.46K. HFU1 - prot.mode, HFU2 - 2.42A.
lm02.Quench.071207121653.161	**72**	18665	2.56	75	-0.007	9.33	4.48	4.49	quench at 18650A at ramp rate 75A/s. 4.44K. HFU2: 2.42A.
lm02.Quench.071207124532.918	**73**	18766	2.59	75	-0.009	10.29	4.48	4.49	Quench at 18752.6A with ramp rate 75A/s. 4.44K. HFU2: 2.45A.
lm02.Quench.071207145654.796	**74**	18831	2.59	75	-0.002	7.77	4.47	4.49	quench at 18815A with ramp rate 75A/s. 4.45K. HFU2: 2.45A.
lm02.Quench.071207153436.267	**75**	18823	2.59	75	-0.002	7.66	4.47	4.49	quench at 18809A with ramp rate 75A/s, 4.44K. HFU2: 2.45A.
lm02.Quench.071207161454.335	**76**	18828	2.59	75	-0.002	7.85	4.48	4.48	quench at 18816A at ramp rate 75A/s. 4.45K. HFU2: 2.45A.
lm02.Quench.071207164953.739	**77**	19023	2.59	20	-0.003	8.40	4.49	4.50	quench at 19010.5A with ramp rate 20A/s (75A/s till 16900A), 4.45K. HFU1 prot.mode, HFU2: 2.45A.
lm02.Quench.071207172704.747	**78**	19489	2.59	20	-0.002	8.17	4.50	4.50	quench at 19479.7A with ramp rate 20A/s (75A/s till 16800A) 4.45K, HFU2: 2.45A.

lm02.Quench.071207175948.575	**79**	19495	2.59	20	-0.002	8.17	4.49	4.50	4.4K, 75A/s to 16700, then 20A/s to quench, with 2.45A on strip htr2 quench at 19480.6 A
lm02.Quench.071207183628.802	**80**	19493	2.59	20	-0.003	8.56	4.49	4.50	quench at 19480.8A, 20A/s, 4.45K. HFU2: 2.45A.
lm02.Quench.071207190929.339	**81**	19505	2.59	20	-0.002	8.18	4.49	4.50	quench at 19490.5A w ramp rate 20A/s (75A/s till 17.5kA) 4.45K HFU2: 2.45A.
lm02.Quench.071208154756.128	**82**	19545	2.56	20	-0.001	7.86	4.51	4.51	quench at 19484A, ramp rate 20A/s (75A/s till 15kA). 4.45K. HFU2: 2.42A.
lm02.Quench.071208162216.260	**83**	19357	2.69	20	-0.001	7.56	4.50	4.52	quench at 19358.2A, 20A/s (75A/s till 16kA) 4.45K. HFU2: 2.55A.
lm02.Quench.071208173445.513	**84**	19555	2.5	20	0.000	7.67	4.49	4.50	quench at 19578.4A at 20A/s (75A/s till 17.5kA). 4.45K. HFU2: 2.36A.
lm02.Quench.071208192634.648	**85**	19583	2.5	20	-0.002	8.22	4.47	4.49	quench at 19569.4A, 20A/s (75A/s till 17.5kA). 4.43K. HFU2: 2.36A.
lm02.Quench.071210100034.144	**-**	409		50	-0.006	0.09	4.44	4.44	low current trip during the test of PS regulator
lm02.Quench.071210110859.095	**86**	19599	2.5	20	-0.005	9.51	4.48	4.50	quench at 19589A, 20A/s (was 75A/s till 17.5kA). 4.44K. HFU2: 2.36A.
lm02.Quench.071210125519.895	**87**	19611	2.5	20	-0.002	8.30	4.46	4.48	quench at 19598.4A with ramp rate 20A/s. 4.44K. (75A/s till 17.8kA), HFU2: 2.36A.
lm02.Quench.071210144109.446	**88**	19698	2.4	20	-0.002	8.30	4.48	4.50	quench at 19688.9A, 20A/s (75A/s till 17.8kA), 4.44K. HFU2: 2.26A.
lm02.Quench.071210153137.309	**89**	19789	2.32	20	-0.003	11.14	4.49	4.47	quench at 19788.5A @ 20A/s (75A/s until 18kA), HFU2: 2.18A
lm02.Quench.071210162719.496	**90**	16803	2.18	75	-0.015	10.31	4.46	4.47	quench at 16795.1A at 75A/s. 4.44K, HFU2: 2.04A.
lm02.Quench.071210170225.658	**91**	16683	2.24	75	-0.013	9.73	4.46	4.46	quench at 16765A, 75A/s. 4.44K. HFU2: 2.1A.
lm02.Quench.071210174722.107	**92**	19781	2.32	20	-0.002	8.27	4.49	4.50	quench at 19766.5A, 20A/s (75A/s till 17kA). 4.46K. HFU2: 2.18A.
lm02.Quench.071210183118.923	**93**	19350	2.18	20	-0.005	9.16	4.48	4.50	quench at 19337.5A 20A/s (75A/s till 17kA) 4.45K. HFU2: 2.18A till 19kA and 2.07A until quench.567
lm02.Quench.071211115744.289	**94**	19375	2.32	20	-0.006	9.51	4.47	4.49	quench at 19360A with ramp rate 20A/s (75A/s till 17.8kA) 4.44K HFU2: 2.186A
lm02.Quench.071211125352.956	**95**	19742	2.37	20	-0.002	8.33	4.49	4.50	quench at 19731.3A at 20A/s (50A/s till 17.5kA). 4.45K. HFU2 2.23A.
lm02.Quench.071211145937.885	**96**	19910	2.37	10	-0.002	8.39	4.48	4.50	quench at 19895.7A with ramp rate 10A/s (75A/s till 18kA). 4.43K. HFU2: 2.23A.
lm02.Quench.071211155106.029	**97**	17873	2.37	75	-0.026	15.09	4.46	4.48	quench at 17865A, ramp rate 75A/s, 4.45K. HFU2: 2.23A.
lm02.Quench.071211162342.275	**98**	18280	2.37	50	-0.009	10.00	4.46	4.48	quench at 18270.6A with ramp rate 50A/s. 4.45K. HFU2: 2.23A.

lm02.Quench.071211175142.035	**99**	19306	2.37	50	-0.009	10.63	4.46	4.48	quench at 19293A with ramp rate 50A/s (75A/s till 15kA). 4.43K. HFU2: 2.23A.
lm02.Quench.071211185217.684	**100**	18143	2.37	100	-0.002	7.42	4.45	4.46	quench at 18098.3A at 100A/s. 4.44K. HFU2: 2.23A.
lm02.Quench.071211192407.108	**101**	11836	2.37	200	-0.005	4.45	4.44	4.44	quench at 11827.6A with rate 200A/s. 4.43K. HFU2: 2.23A.
lm02.Quench.071211195021.105	**102**	4218	0	200	-0.077	2.06	4.43	4.44	quench at 2886.3A with rate 200A/s. 4.45K. No current on HFU2
lm02.Quench.071211202352.114	**103**	19903	2.37	5	-0.003	8.71	0.00	0.00	Data was lost
lm02.Quench.071212093439.012	**104**	20106	2.38	5	-0.002	8.53	4.49	4.51	quench at 20090.3A with ramp rate 5A/s. 4.44K. HFU2: 2.24A.
lm02.Quench.071212100126.233	**105**	17331	2.38	125	-0.003	7.37	4.46	4.47	quench at 17320A with ramp rate 125A/s. 4.45K. HFU2: 2.24A.
lm02.Quench.071212103802.130	**106**	5928	2.38	250	-0.182	7.67	4.45	4.45	quench at 5965.3A with ramp rate 250A/s. 4.45K. HFU2: 2.24A.
Test Cycle II									
lm02.Quench.080104162639.515	**-**	5012		0	-0.224	7.15	4.45	4.45	HFU2 @250V induced trip at 5000A, HFU1 @300V in protection mode. T=4.45K. Dump delay 25msec.
lm02.Quench.080104175155.842	**107**	16204	0	20	-0.024	12.49	4.46	4.46	quench at ~16.1kA, ramp rate 20A/s, 4.45K. No current on HFU2.
lm02.Quench.080104184713.051	**108**	18939	2.38	20	-0.002	7.99	4.51	4.50	quench at 18914A, 20A/s (50A/s upto 16kA), 4.45K. HFU2: 2.25A.
lm02.Quench.080104194027.433	**109**	19184	2.38	20	-0.002	8.15	4.50	4.49	quench at 19167A ramp rate 20A/s (75A/s upto 17.5kA), 4.44K, HFU2: 2.24A.
lm02.Quench.080104201556.007	**110**	19621	2.38	20	-0.002	8.49	4.50	4.49	quench at 19600A with ramp rate 20A/s (75A/s upto 18kA). HFU2: 2.24A.
lm02.Quench.080108155008.842	**-**	174		75	-0.004	0.04	4.43	4.43	Trip at ~200A, ramp rate was 75A/s
lm02.Quench.080108160531.104	**111**	19590	2.38	20	0.0006	7.28	4.48	4.47	quench at 19475A with ramp rate 20A/s (75A/s upto 18.1kA), HFU2: 2.24A. 4.43K.
lm02.Quench.080108163344.479	**-**	178		75	-0.004	0.04	4.44	4.44	Trip at ~200A again, ramp rate was 75A/s
lm02.Quench.080108164738.206	**112**	19776	2.38	20	-0.002	8.46	4.48	4.48	quench at 19735A with ramp rate 20A/s (75A/s till 18.4kA), 4.44K. HFU2: 2.24A.
lm02.Quench.080108173957.835	**113**	19811	2.38	20	-0.001	7.87	4.48	4.48	quench at 19745A at 4.45K, ramp rate 20A/s (75A/s till 18.4kA) HFU2: 2.24A.
lm02.Quench.080108181942.421	**114**	19610	2.38	20	-0.004	9.21	4.48	4.48	quench at 19578A with ramp rate 20A/s (75A/s upto 18.5kA), HFU2: 2.24A. 4.45K

lm02.Quench.080108190141.332	**115**	19792	2.38	20	-0.003	8.79	4.48	4.48	quench at 19758.3A, 20A/s (75A/s upto 18.5kA), 4.44K, HFU2: 2.24A.
lm02.Quench.080109111509.148	**116**	19710	3.05	20	-0.001	7.83	2.16	2.16	quench at 19743.3A at 2.16K. HFU2: 2.91A. 20A/s (was 75A/s upto 18.2kA)
lm02.Quench.080109120442.240	**117**	19920	2.88	20	0.001	7.54	2.16	2.16	quench at 19923.3A, 20A/s (75A/s upto 18.5kA), HFU2: 2.74A. 2.16K.
lm02.Quench.080109125102.832	**118**	20072	2.88	20	-0.001	7.85	2.16	2.16	quench at 20072.3A, 20A/s (75A/s upto 18.5kA), HFU2: 2.74A. 2.16K.
lm02.Quench.080109141345.234	**119**	20067	2.88	20	-0.001	7.99	2.16	2.16	quench at 20038A, 20A/s (75A/s upto 18.5kA), HFU2: 2.74A, 2.16K.
lm02.Quench.080109154130.388	**120**	20243	2.7	20	-0.002	8.56	2.16	2.16	quench at 20216A, 20A/s (75A/s upto 18.6kA) HFU2: 2.56A. 2.16K.
lm02.Quench.080109162437.434	**121**	20196	2.7	20	-0.002	8.59	2.16	2.16	quench at 20.2kA, 20A/s (75kA upto 18.6kA) HFU2: 2.56A.
lm02.Quench.080109170211.795	**122**	20316	2.7	20	-0.002	8.61	2.16	2.16	quench at 20295A, 20A/s (75A/s upto 18.6kA), 2.16K. HFU2: 2.56A.
lm02.Quench.080110093739.224	**123**	20281	2.7	20	-0.002	8.82	2.16	2.16	quench at 20270.5A with ramp rate 20A/s (75A/s upto 18.6kA), 2.16K. HFU2: 2.56A.
lm02.Quench.080110101902.974	**124**	19288	2.53	20	-0.007	10.01	2.16	2.16	quench at 19277A, 20A/s (75A/s upto 18kA) 2.16K HFU2: 2.39A.
lm02.Quench.080110105443.858	**125**	20463	2.6	20	-0.002	8.80	2.16	2.16	quench at 20450.5A with ramp rate 20A/s (75A/s upto 18.6kA). 2.16K. HFU2: 2.46A.
lm02.Quench.080110113126.904	**126**	19516	2.6	20	-0.006	9.82	2.16	2.16	quench at 19505A with ramp rate 20A/s (75A/s upto 19kA) 2.16K. HFU2: 2.46
lm02.Quench.080110121945.213	**127**	15608	2.64	175	-0.003	6.37	2.16	2.16	quench at 15599A with ramp rate 175A/s. HFU2: 2.5A. 2.16K.
lm02.Quench.080110124104.634	**128**	13342	2.64	200	-0.015	7.08	2.16	2.16	quench at 13334.4A with ramp rate 200A/s. 2.16K. HFU2: 2.5A.
lm02.Quench.080110130152.414	**129**	10086	2.64	225	-0.006	3.55	2.16	2.16	quench at 10080A with ramp rate 225A/s. 2.16K. HFU2: 2.5A.
lm02.Quench.080110131321.997	**130**	6470	2.64	250	-0.016	2.10	2.16	2.15	quench at 6466A with ramp rate 250A/s. HFU2: 2.5A. 2.16K.
lm02.Quench.080110135520.237	**131**	18317	2.64	125	-0.002	7.59	2.16	2.16	quench at 18309.2A with ramp rate 125A/s. HFU2: 2.5A. 2.16K.
lm02.Quench.080110143958.566	**132**	3646	2.64	250	-0.067	1.42	2.15	2.15	Ramp rate 250A/s. HFU2: 2.5A. T=2.16K.
lm02.Quench.080111123214.977	**133**	19337.3	2.64	50	-0.005	9.39	2.16	2.16	quench at 19324A with ramp rate 50A/s (75A/s to 18kA), HFU2: 2.5A. 2.16K.
lm02.Quench.080111132418.931	**134**	17877.9	2.64	50	-0.013	10.75	2.16	2.16	quench at 17870A, seems in outer layer. 50A/s. 2.16K. HFU2: 2.5A.
lm02.Quench.080111140906.098	**135**	20633.3	2.64	10	-0.002	8.61	2.17	2.16	quench at 20625A with ramp rate 10A/s (75A/s upto 18.5kA), 2.16K. HFU2: 2.5A.

lm02.Quench.080111161459.441	**136**	16742.5	2.38	75	-0.011	9.39	3.05	3.22	quench at 16732.5A with ramp rate 75A/s. 3.1K. HFU2: 2.23A.
lm02.Quench.080111165055.635	**137**	20149.6	2.58	20	-0.001	8.11	3.01	3.25	quench at 20160A with ramp rate 20A/s (75A/s upto 17kA), 3.1K, HFU2: 2.43A
lm02.Quench.080111172621.006	**138**	20073.4	2.68	20	-0.002	8.39	3.03	3.22	quench at 20065A with ramp rate 20A/s (75A/s upto 18kA), 3.1K, HFU2: 2.53A.
lm02.Quench.080111180918.411	**139**	20328.6	2.49	20	-0.001	7.99	2.98	3.32	quench at 20317.7A with ramp rate 20A/s (75A/s upto 18.2kA), 3.0K, HFU2: 2.34A.
lm02.Quench.080111183945.329	**140**	19810.9	2.88	20	-0.002	8.35	3.00	3.12	quench at 19800.6A at 20A/s (75A/s upto 18kA), 3K, HFU2: 2.73A.
lm02.Quench.080112102344.905	**141**	7404.3	2.39	225	-0.049	4.54	4.45	4.44	quench at 7410.3A with ramp rate 225A/s. 4.5K. HFU2: 2.22A.
lm02.Quench.080112110002.089	**142**	14208.4	2.39	175	-0.003	5.57	4.45	4.45	quench at 14200.2A with ramp rate 175A/s. 4.44K. HFU2: 2.22A (offset +0.17A).
lm02.Quench.080112114927.983	**143**	19715.4	2.39	20	-0.002	8.44	4.44	4.44	ramp rate 20A/s (75A/s upto 18.6kA) 4.4K, HFU2: 2.22A
lm02.Quench.080112124056.510	**144**	20706.3	2.39 (0 after 19kA)	10	-0.002	5.57	4.43	4.43	ramp rate 10A/s (75A/s upto 18.5kA), 4.43K, HFU2: 2.23A and was set to 0A at 19kA.

Table 2: LM02 Quench History with parameters for the first two quenching segments

File	#	Current (A)	dI/dt (A/sec)	t_{quench}	QDC	1st VTseg	t_{rise}	2nd VTseg	t_{rise}	Mag Temp Bot	Mag Temp Top
Test Cycle I											
lm02.Quench.071119130323.653	**-**	5005	100	-0.162	HcoilHcoil	6ou_os30	-0.0209	is30b_3aub	-0.0057	4.43	4.43
lm02.Quench.071119142541.269	**-**	5005	100	-0.155	HcoilHcoil	11ou_6ou	-0.0193	cc_ispc	-0.0077	4.43	4.42
lm02.Quench.071119145855.028	**1**	14971	20	-0.021	HcoilHcoil	is30_3au	-0.0169	3au_8au	-0.0062	4.44	4.43
lm02.Quench.071119153259.338	**-**	5280	20	-0.056	HcoilHcoil	8au_11lel	-0.0045	11ou_6ou	-0.0003	4.43	4.43
lm02.Quench.071119163859.701	**2**	16322	20	-0.041	HcoilHcoil	6ou_os30	-0.0405			4.43	4.43
lm02.Quench.071119171751.104	**3**	16599	20	-0.044	HcoilHcoil	6ou_os30	-0.0235	cc_ispc	-0.0017	4.44	4.43
lm02.Quench.071119181756.420	**4**	15074	20	-0.042	HcoilHcoil	6ou_os30	-0.0420			4.44	4.43
lm02.Quench.071119185103.187	**5**	15961	20	-0.042	HcoilHcoil	6ou_os30	-0.0321			4.43	4.43
lm02.Quench.071119192825.509	**6**	16826	20	-0.007	HcoilHcoil					4.43	4.43
lm02.Quench.071120095152.786	**-**	2286	?	-0.549	HcoilHcoil	is31_is30	-0.0013	11rel_cc	-0.0007	4.43	4.42
lm02.Quench.071120103537.292	**7**	15703	20	-0.034	HcoilHcoil	6ou_os30	-0.0300			4.44	4.43
lm02.Quench.071120112938.135	**8**	16340	20	-0.004	HcoilHcoil	11lel_11ler	-0.0064	11ler_11rer	-0.0042	4.43	4.44
lm02.Quench.071120122407.002	**9**	15641	20	-0.022	HcoilHcoil	6ou_os30	-0.009			4.43	4.43
lm02.Quench.071120131733.411	**10**	17083	20	-0.011	HcoilHcoil	6ou_os30	-0.0115			4.43	4.44
lm02.Quench.071120150123.608	**11**	16376	20	-0.020	HcoilHcoil	6ou_os30	-0.022			4.44	4.43
lm02.Quench.071120154432.849	**12**	16067	20	-0.033	HcoilHcoil	6ou_os30	-0.0224			4.44	4.44
lm02.Quench.071120163503.638	**13**	15928	20	-0.040	HcoilHcoil	6ou_os30	-0.0266			4.44	4.44
lm02.Quench.071120170718.983	**14**	15995	20	-0.024	HcoilHcoil	6ou_os30	-0.026			4.43	4.43
lm02.Quench.071120180456.296	**15**	5171	300	-0.026	HcoilHcoil	6ou_os30	-0.0285	is30_3au	-0.0285	4.42	4.42

lm02.Quench.071120185422.368	**16**	2448	250	-0.603	HcoilHcoil	is31_is30	-0.0028	cc_ispc	0.0008	4.42	4.42
lm02.Quench.071120193128.628	**17**	2631	250	-0.434	WcoilIdot	is31_is30	-0.0027	ic_is31	0.0011	4.42	4.42
lm02.Quench.071120194619.494	**18**	2754	200	-0.357	WcoilIdot	is31_is30	-0.0018	ic_is31	0.0017	4.42	4.42
lm02.Quench.071120201402.612	**19**	13863	200	-0.006	HcoilHcoil	3au_8au	-0.0078	11ou_6ou	-0.0078	4.43	4.43
lm02.Quench.071120203347.678	**20**	4773	150	-0.312	HcoilHcoil	is30b_3aub	-0.0484	is30_3au	-0.0413	4.42	4.42
lm02.Quench.071120204915.176	**21**	6781	300	-0.014	HcoilHcoil	is30b_3aub	-0.0146	is30_3au	-0.0144	4.43	4.42
lm02.Quench.071121114634.526	**-**	1004	20	0.011	GndRef	11ou_6ou	0.0154	8au_11lel	0.0155	4.43	4.42
lm02.Quench.071121122741.214	**22**	15663	20	-0.046	HcoilHcoil	6ou_os30	-0.0252			4.43	4.44
lm02.Quench.071121150510.382	**23**	7973	300	-0.014	HcoilHcoil	is30_3au	-0.0122	3au_8au	-0.0102	4.43	4.43
lm02.Quench.071121153631.684	**24**	8075	250	-0.168	HcoilHcoil	is30_3au	-0.0112	6ou_os30	-0.0102	4.43	4.43
lm02.Quench.071121163004.596	**25**	13605	200	-0.003	WcoilIdot	is30_3au	-0.0049	3au_8au	-0.0049	4.43	4.43
lm02.Quench.071121172131.773	**26**	16498	150	-0.002	HcoilHcoil	3au_8au	-0.0033	11lel_11ler	-0.003	4.44	4.43
lm02.Quench.071121181548.267	**27**	15536	100	-0.041	HcoilHcoil	6ou_os30	-0.029	11ou_6ou	-0.029	4.43	4.43
lm02.Quench.071121192932.608	**28**	14642	4	-0.040	HcoilHcoil	6ou_os30	-0.024			4.44	4.44
lm02.Quench.071123091720.493	**29**	15635	50	-0.039	HcoilHcoil	6ou_os30	-0.022			4.45	4.44
lm02.Quench.071123133325.864	**30**	16825	75	-0.013	HcoilHcoil	6ou_os30	-0.0106			4.45	4.45
lm02.Quench.071123143419.163	**31**	15591	10	-0.039	HcoilHcoil	6ou_os30	-0.026			4.45	4.45
lm02.Quench.071123164637.194	**32**	3905	200	-0.139	HcoilHcoil	6ou_os30	-0.15	is30_3au	-0.15	4.43	4.43
lm02.Quench.071123180710.753	**33**	14919	5	-0.030	HcoilHcoil	6ou_os30	-0.022			4.45	4.45
lm02.Quench.071124104716.201	**34**	16390	20	-0.003	GndRef	is30_3au	-0.0045			2.15	2.15
lm02.Quench.071124113231.661	**35**	15935	20	-0.024	HcoilHcoil	6ou_os30	-0.017			2.15	2.15
lm02.Quench.071124122232.602	**36**	16512	20	-0.003	HcoilHcoil	is30_3au	-0.0049			2.15	2.15
lm02.Quench.071124132800.667	**37**	4934	150	-0.029	WcoilIdot	6ou_os30	-0.034	is30_3au	-0.034	2.15	2.15
lm02.Quench.071124140104.263	**38**	16139	150	-0.017	HcoilHcoil	6ou_os30	-0.0167			2.16	2.15
lm02.Quench.071124151130.190	**39**	4035	250	-0.054	WcoilIdot	6ou_os30	-0.056	is30_3au	-0.056	2.15	2.15
lm02.Quench.071124152623.690	**40**	3013	250	-0.079	WcoilIdot	6ou_os30	-0.084	is30_3au	-0.084	2.15	2.15
lm02.Quench.071126100235.880	**41**	3587	200	0.000						2.15	2.15
lm02.Quench.071126120537.599	**42**	15813	20	-0.028	HcoilHcoil	6ou_os30	-0.0276			2.15	2.15

lm02.Quench.071126130008.144	**43**	3464	200	-0.255	HcoilHcoil	6ou_os30	-0.057	is30_3au	-0.0570	2.14	2.15
lm02.Quench.071126143040.829	**44**	16652	100	-0.004	HcoilHcoil	is30_3au	-0.0033			2.16	2.15
lm02.Quench.071126152519.792	**45**	16250	74	-0.022	HcoilHcoil	6ou_os30	-0.0179			2.16	2.15
lm02.Quench.071126160256.532	**46**	16398	50	-0.025	HcoilHcoil	6ou_os30	-0.022			2.15	2.15
lm02.Quench.071126173753.954	**47**	14096	4	-0.006	HcoilHcoil	is30_3au	-0.011			2.15	2.15
lm02.Quench.071126185952.423	**48**	15736	100	-0.027	HcoilHcoil	6ou_os30	-0.029			2.16	2.16
lm02.Quench.071127093039.799	**49**	16230	10	-0.015	HcoilHcoil	6ou_os30	-0.02			2.15	2.15
lm02.Quench.071127103015.457	**50**	15873	175	-0.027	HcoilHcoil	6ou_os30	-0.028			2.16	2.15
lm02.Quench.071127104723.092	**51**	2910	300	-0.391	HcoilHcoil	is30_3au	-0.028	6ou_os30	-0.0280	2.15	2.15
lm02.Quench.071127120138.030	**52**	17098	20	-0.161	HcoilHcoil	6ou_os30	-0.012			2.15	2.15
lm02.Quench.071129150553.178	**-**	198	10	-0.003	WcoilGnd	11ou_6ou	0.0006	11rel_cc	0.0006	4.00	4.26
lm02.Quench.071130115729.273	**-**	197	20	-0.007	WcoilGnd	6ou_os30	-0.0017	is30_3au	-0.0017	4.21	4.33
lm02.Quench.071203125619.345	**53**	16549	20	-0.024	HcoilHcoil	6ou_os30	-0.0241			2.16	2.16
lm02.Quench.071203160128.335	**54**	16970	20	-0.003	HcoilHcoil	is30_3au	-0.0039			2.16	2.16
lm02.Quench.071203164257.645	**55**	16842	20	-0.020	HcoilHcoil	6ou_os30	-0.021			2.16	2.16
lm02.Quench.071203175459.996	**56**	15014	0	-0.021	HcoilHcoil	6ou_os30	-0.02			2.17	2.16
lm02.Quench.071203183601.753	**57**	15789	20	-0.004	HcoilHcoil	is30_3au	-0.0058			2.16	2.16
lm02.Quench.071203191758.994	**58**	15738	20	-0.003	HcoilHcoil	is30_3au	-0.006			2.17	2.16
lm02.Quench.071204101939.213	**59**	16702	20	-0.017	HcoilHcoil	6ou_os30	-0.0168			2.17	2.16
lm02.Quench.071204112239.628	**60**	16128	20	-0.016	HcoilHcoil	6ou_os30	-0.0165			2.17	2.16
lm02.Quench.071204114718.483	**61**	3514	175	-0.180	WcoilIdot	is30_3au	-0.209	6ou_os30	-0.209	2.16	2.16
lm02.Quench.071204164622.585	**62**	17240	150	-0.004	HcoilHcoil	3au_8au	-0.004			4.43	4.43
lm02.Quench.071204182026.624	**63**	14158	200	-0.006	HcoilHcoil	3au_8au	-0.0055			4.43	4.43
lm02.Quench.071204183645.423	**64**	17097	150	-0.015	HcoilHcoil	6ou_os30	-0.0094			4.43	4.43
lm02.Quench.071206110830.848	**65**	15764	75	-0.021	HcoilHcoil	6ou_os30	-0.0175			4.45	4.45
lm02.Quench.071206160652.262	**66**	17205	75	-0.007	HcoilHcoil	6ou_os30	-0.0118			4.45	4.45
lm02.Quench.071206165145.240	**67**	17200	75	-0.012	HcoilHcoil	6ou_os30	-0.0127			4.47	4.47

lm02.Quench.071206171848.743	**-**	184	75	-0.004	HcoilHcoil	11ou_6ou	0.002	11rel_cc	0.002	4.48	4.47
lm02.Quench.071206173247.770	**68**	17204	75	-0.013	WcoilGnd	6ou_os30	-0.0138	11ou_6ou	-0.0035	4.48	4.48
lm02.Quench.071206184456.470	**69**	18199	75	-0.002	HcoilHcoil	11rel_cc	-0.0035	11rer_11rel	-0.0025	4.48	4.49
lm02.Quench.071206193612.436	**70**	18131	75	-0.268	HcoilHcoil	6ou_os30	-0.009			4.50	4.50
lm02.Quench.071207114658.721	**71**	18607	75	-0.003	HcoilHcoil	6ou_os30	-0.007			4.50	4.50
lm02.Quench.071207121653.161	**72**	18665	75	-0.007	HcoilHcoil	6ou_os30	-0.005			4.48	4.49
lm02.Quench.071207124532.918	**73**	18766	75	-0.009	HcoilHcoil	6ou_os30	-0.0054			4.47	4.49
lm02.Quench.071207145654.796	**74**	18831	75	-0.002	HcoilHcoil	3au_8au	-0.0047	6ou_os30	-0.0025	4.48	4.48
lm02.Quench.071207153436.267	**75**	18823	75	-0.002	HcoilHcoil	3au_8au	-0.0042	6ou_os30	-0.0025	4.47	4.49
lm02.Quench.071207161454.335	**76**	18828	75	-0.002	HcoilHcoil	3au_8au	-0.0042	11lel_11ler	-0.0015	4.47	4.49
lm02.Quench.071207164953.739	**77**	19023	20	-0.003	HcoilHcoil	3au_8au	-0.0042	11ou_6ou	-0.0018	4.48	4.48
lm02.Quench.071207172704.747	**78**	19489	20	-0.002	HcoilHcoil	3au_8au	-0.0026	11rel_cc	-0.0009	4.48	4.50
lm02.Quench.071207175948.575	**79**	19495	20	-0.002	HcoilHcoil	is30_3au	-0.004	3au_8au	-0.001	4.50	4.50
lm02.Quench.071207183628.802	**80**	19493	20	-0.003	HcoilHcoil	is30_3au	-0.003	3au_8au	-0.0011	4.49	4.50
lm02.Quench.071207190929.339	**81**	19505	20	-0.002	WcoilIdot	is30_3au	-0.0035	3au_8au	-0.0014	4.49	4.50
lm02.Quench.071208154756.128	**82**	19545	20	-0.001	HcoilHcoil	is30_3au	-0.0033	3au_8au	-0.0018	4.48	4.50
lm02.Quench.071208162216.260	**83**	19357	20	-0.001	WcoilIdot	is30_3au	-0.0022	3au_8au	-0.001	4.50	4.51
lm02.Quench.071208173445.513	**84**	19555	20	0.000	WcoilIdot	is30_3au	-0.0034	3au_8au	-0.0012	4.50	4.52
lm02.Quench.071208192634.648	**85**	19583	20	-0.002	WcoilIdot	is30_3au	-0.0024	3au_8au	-0.0011	4.49	4.50
lm02.Quench.071210100034.144	**-**	409	50	-0.006	HcoilHcoil	8au_11lel	0.0015	11ou_6ou	0.0017	4.47	4.49
lm02.Quench.071210110859.095	**86**	19599	20	-0.005	WcoilGnd	is30_3au	-0.003	3au_8au	-0.0012	4.44	4.44
lm02.Quench.071210125519.895	**87**	19611	20	-0.002	WcoilGnd	is30_3au	-0.0028	3au_8au	-0.0007	4.48	4.50
lm02.Quench.071210144109.446	**88**	19698	20	-0.002	HcoilHcoil	is30_3au	-0.0021	3au_8au	-0.0010	4.46	4.48
lm02.Quench.071210153137.309	**89**	19789	20	-0.003	HcoilHcoil	is30_3au	-0.0025	3au_8au	-0.0009	4.48	4.49
lm02.Quench.071210162719.496	**90**	16803	75	-0.015	HcoilHcoil	6ou_os30	-0.02			4.46	4.47
lm02.Quench.071210170225.658	**91**	16683	75	-0.013	HcoilHcoil	6ou_os30	-0.016			4.46	4.46
lm02.Quench.071210174722.107	**92**	19781	20	-0.002	HcoilHcoil	is30_3au	-0.0038	3au_8au	-0.0012	4.49	4.50
lm02.Quench.071210183118.923	**93**	19350	20	-0.005	HcoilHcoil	6ou_os30	-0.006			4.48	4.49

lm02.Quench.071211115744.289	**94**	19375	20	-0.006	HcoilHcoil	6ou_os30	-0.006			4.47	4.49
lm02.Quench.071211125352.956	**95**	19742	20	-0.002	HcoilHcoil	is30_3au	-0.0034	3au_8au	-0.0015	4.48	4.50
lm02.Quench.071211145937.885	**96**	19910	10	-0.002	HcoilHcoil	11rel_cc	-0.0039	8au_11lel	-0.0030	4.48	4.50
lm02.Quench.071211155106.029	**97**	17873	75	-0.026	HcoilHcoil	6ou_os30	-0.016			4.46	4.47
lm02.Quench.071211162342.275	**98**	18280	50	-0.009	HcoilHcoil	6ou_os30	-0.0095			4.46	4.48
lm02.Quench.071211175142.035	**99**	19306	50	-0.009	HcoilHcoil	6ou_os30	-0.005			4.46	4.48
lm02.Quench.071211185217.684	**100**	18143	100	-0.002	HcoilHcoil	3au_8au	-0.0045	11ler_11rer	-0.0015	4.45	4.46
lm02.Quench.071211192407.108	**101**	11836	200	-0.005	HcoilHcoil	3au_8au	-0.0072	is30_3au	-0.0067	4.44	4.44
lm02.Quench.071211195021.105	**102**	4218	200	-0.077	HcoilHcoil	6ou_os30	-0.044	is30_3au	-0.0440	4.43	4.43
lm02.Quench.071211202352.114	**103**	19903	5	-0.003	HcoilHcoil					4.43	4.43
lm02.Quench.071212093439.012	**104**	20106	5	-0.002	HcoilHcoil	3au_8au	-0.0035	11ler_11rer	-0.0021	4.49	4.50
lm02.Quench.071212100126.233	**105**	17331	125	-0.003	HcoilHcoil	3au_8au	-0.0046	is30_3au	-0.0033	4.46	4.46
lm02.Quench.071212103802.130	**106**	5928	250	-0.182	HcoilHcoil	is30_3au	-0.021	6ou_os30	-0.0210	4.45	4.44
Test Cycle II											
lm02.Quench.080104162639.515	**-**	5012	0	-0.224	HcoilHcoil	6ou_os30	-0.2220			4.45	4.45
lm02.Quench.080104175155.842	**107**	16204	20	-0.024	HcoilHcoil	6ou_os30	-0.0244			4.46	4.46
lm02.Quench.080104184713.051	**108**	18939	20	-0.002	HcoilHcoil	8au_11lel	-0.0043	11lel_11ler	-0.0040	4.51	4.50
lm02.Quench.080104194027.433	**109**	19184	20	-0.002	HcoilHcoil	11ler_11rer	-0.0036	11lel_11ler	-0.0033	4.50	4.49
lm02.Quench.080104201556.007	**110**	19621	20	-0.002	HcoilHcoil	3au_8au	-0.0031	11rel_cc	-0.0007	4.50	4.49
lm02.Quench.080108155008.842	**-**	174	75	-0.004	WcoilGnd	11ou_6ou	-0.0028	8au_11lel	-0.0028	4.43	4.43
lm02.Quench.080108160531.104	**111**	19590	20	0.001	WcoilIdot	11lel_11ler	-0.0036	11ler_11rer	-0.0030	4.48	4.47
lm02.Quench.080108163344.479	**-**	178	75	-0.004	WcoilGnd	8au_11lel	-0.0029	11ou_6ou	-0.0028	4.44	4.44
lm02.Quench.080108164738.206	**112**	19776	20	-0.002	WcoilIdot	is30_3au	-0.0035	3au_8au	-0.0012	4.48	4.48
lm02.Quench.080108173957.835	**113**	19811	20	-0.001	WcoilIdot	is30_3au	-0.0036	3au_8au	-0.0015	4.48	4.48
lm02.Quench.080108181942.421	**114**	19610	20	-0.004	HcoilHcoil	3au_8au	-0.0032	is30_3au	-0.0015	4.48	4.48
lm02.Quench.080108190141.332	**115**	19792	20	-0.003	WcoilGnd	is30_3au	-0.0035	3au_8au	-0.0011	4.48	4.48
lm02.Quench.080109111509.148	**116**	19710	20	-0.001	WcoilIdot	is30_3au	-0.0032	3au_8au	-0.0012	2.16	2.16
lm02.Quench.080109120442.240	**117**	19920	20	0.001	WcoilIdot	11rel_cc	-0.0045	8au_11lel	-0.0028	2.16	2.16

lm02.Quench.080109125102.832	**118**	20072	20	-0.001	WcoilIdot	is30_3au	-0.0034	3au_8au	-0.0008	2.16	2.16
lm02.Quench.080109141345.234	**119**	20067	20	-0.001	WcoilIdot	is30_3au	-0.0035	3au_8au	-0.0010	2.16	2.16
lm02.Quench.080109154130.388	**120**	20243	20	-0.002	HcoilHcoil	is30_3au	-0.0029	3au_8au	-0.0007	2.16	2.16
lm02.Quench.080109162437.434	**121**	20196	20	-0.0018	HcoilHcoil	11rer_11rel	-0.0034	11ler_11rer	-0.0029	2.16	2.16
lm02.Quench.080109170211.795	**122**	20316	20	-0.0018	HcoilHcoil	is30_3au	-0.0037	3au_8au	-0.0012	2.16	2.16
lm02.Quench.080110093739.224	**123**	20281	20	-0.0022	HcoilHcoil	is30_3au	-0.0033	3au_8au	-0.0010	2.16	2.16
lm02.Quench.080110101902.974	**124**	19288	20	-0.0070	HcoilHcoil	6ou_os30	-0.0065			2.16	2.16
lm02.Quench.080110105443.858	**125**	20463	20	-0.0021	HcoilHcoil	is30_3au	-0.0032	3au_8au	-0.0010	2.16	2.16
lm02.Quench.080110113126.904	**126**	19516	20	-0.0060	HcoilHcoil	6ou_os30	-0.0060			2.16	2.16
lm02.Quench.080110121945.213	**127**	15608	175	-0.0032	HcoilHcoil	3au_8au	-0.0048	11rel_cc	-0.0023	2.16	2.16
lm02.Quench.080110124104.634	**128**	13342	200	-0.0147	WcoilGnd	3au_8au	-0.0057	11rel_cc	-0.0023	2.16	2.16
lm02.Quench.080110130152.414	**129**	10086	225	-0.0060	HcoilHcoil	3au_8au	-0.0080			2.16	2.16
lm02.Quench.080110131321.997	**130**	6470	250	-0.0161	HcoilHcoil	3au_8au	-0.0155	11ou_6ou	-0.0105	2.16	2.15
lm02.Quench.080110135520.237	**131**	18317	125	-0.0020	HcoilHcoil	3au_8au	-0.0043	is30_3au	-0.0027	2.16	2.16
lm02.Quench.080110143958.566	**132**	3646	250	-0.0673	WcoilIdot	6ou_os30	-0.0684	11ou_6ou	-0.0564	2.15	2.15
lm02.Quench.080111123214.977	**133**	19337.3	50	-0.005	HcoilHcoil	6ou_os30	-0.0066			2.16	2.16
lm02.Quench.080111132418.931	**134**	17877.9	50	-0.0125	HcoilHcoil	6ou_os30	-0.0095			2.16	2.16
lm02.Quench.080111140906.098	**135**	20633.3	10	-0.001	HcoilHcoil	is30_3au	-0.0029	3au_8au	-0.0014	2.17	2.16
lm02.Quench.080111161459.441	**136**	16742.5	75	-0.011	WcoilIdot	6ou_os30	-0.0111			3.22	3.22
lm02.Quench.080111165055.635	**137**	20149.6	20	-0.001	WcoilIdot	is30_3au	-0.0033	3au_8au	-0.0011	3.25	3.25
lm02.Quench.080111172621.006	**138**	20073.4	20	-0.002	WcoilIdot	is30_3au	-0.0035	3au_8au	-0.001	3.03	3.30
lm02.Quench.080111180918.411	**139**	20328.6	20	-0.001	WcoilIdot	is30_3au	-0.0032	3au_8au	-0.0012	3.32	3.32
lm02.Quench.080111183945.329	**140**	19810.9	20	-0.002	HcoilHcoil	is30_3au	-0.0032	3au_8au	-0.0012	3.00	3.12
lm02.Quench.080112102344.905	**141**	7404.3	225	-0.049	WcoilGnd	is30_3au	-0.0141	3au_8au	-0.0129	4.45	4.44
lm02.Quench.080112110002.089	**142**	14208.4	175	-0.003	WcoilIdot	3au_8au	-0.0056	is30_3au	-0.0051	4.45	4.45
lm02.Quench.080112114927.983	**143**	19715.4	20	-0.002	HcoilHcoil	is30_3au	-0.0037	3au_8au	-0.0012	4.44	4.44
lm02.Quench.080112124056.510	**144**	20706.3	10	-0.002	HcoilHcoil	is30_3au	-0.0034	3au_8au	-0.001	4.43	4.43

3. Test with the strip heater

An initial stage of the test showed quench current limitation in the outer layer mid-plane segment of the LM02 magnet. Magnetic field calculation shows (Fig.7, top left) the lowest magnetic field is in the above-mentioned block at any current. Erratic quench performance with the quench currents far away from the expected limits and with no signs of training may be explained with the magnetic instability in this very low field region. A possible way of checking this hypothesis was to change the conductor conditions which might affect the instability. For example, warming up the local conductor could effectively reduce its critical current density J_c locally and therefore make it less susceptible to the instabilities. As a source of heat, one could use the strip heater conveniently located next to the mid-plane block of the outer coil, which was originally installed for the magnet protection.

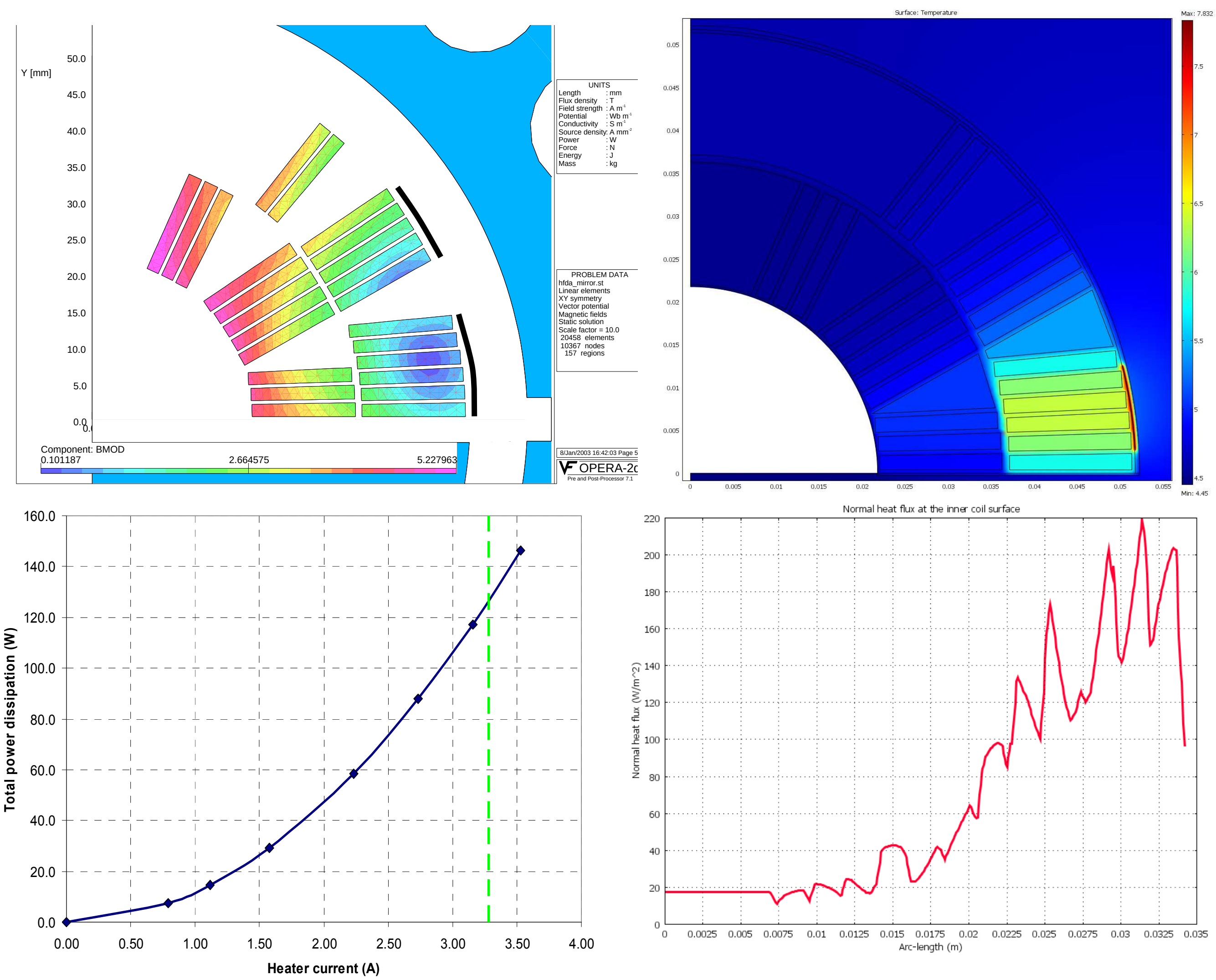


Fig.7 Magnetic field (top left) and temperature distribution (top right) in the coil cross-section, the total power dissipation as a function of the heater current (bottom left) and the normal heat flux at the inner coil surface at 3.25 A current (bottom right).

Extensive simulation of the magnet thermal parameters was performed using *COMSOL Multiphysics* code in order to estimate the temperature in different coil segments, as well as the total power dissipation as a function of the heater current. The finite-element model included one-half of the magnet cross-section with a constant (helium bath) temperature at the outer yoke boundary and the inner coil boundary that are in direct contact with the liquid helium.

The thermal conductivity of impregnated cable, interlayer, and ground insulation was assumed the same as across the sheet of G10 material. In addition, the coil had a mid-plane shim made of *Kapton* and a *Kapton* tape separating the heater from the cable insulation. The material thermal conductivities were parameterized after [1] in the relevant temperature range. A typical temperature distribution in the coil cross-section is shown in Fig. 7 (top right). With the heater on, the peak coil temperature is in the outer mid-plane block, however, the inner mid-plane block has the lowest quench margin due to the higher field in the inner layer.

During the test we varied the heater current in within 2-3 A corresponding to the total dissipated power from 40 to 100 W (see Fig.7, bottom left). The calculated heat flux at the inner coil surface contact with liquid helium is shown in Fig. 7 (bottom right) at the maximum heater current of 3.25 A. The peak heat flux is 220 W/m^2 for the middle turn of the mid-plane block that is at least an order of magnitude lower than the helium film-boiling threshold. Consequently, no heat-related problems were observed in the cryogenic system during the test.

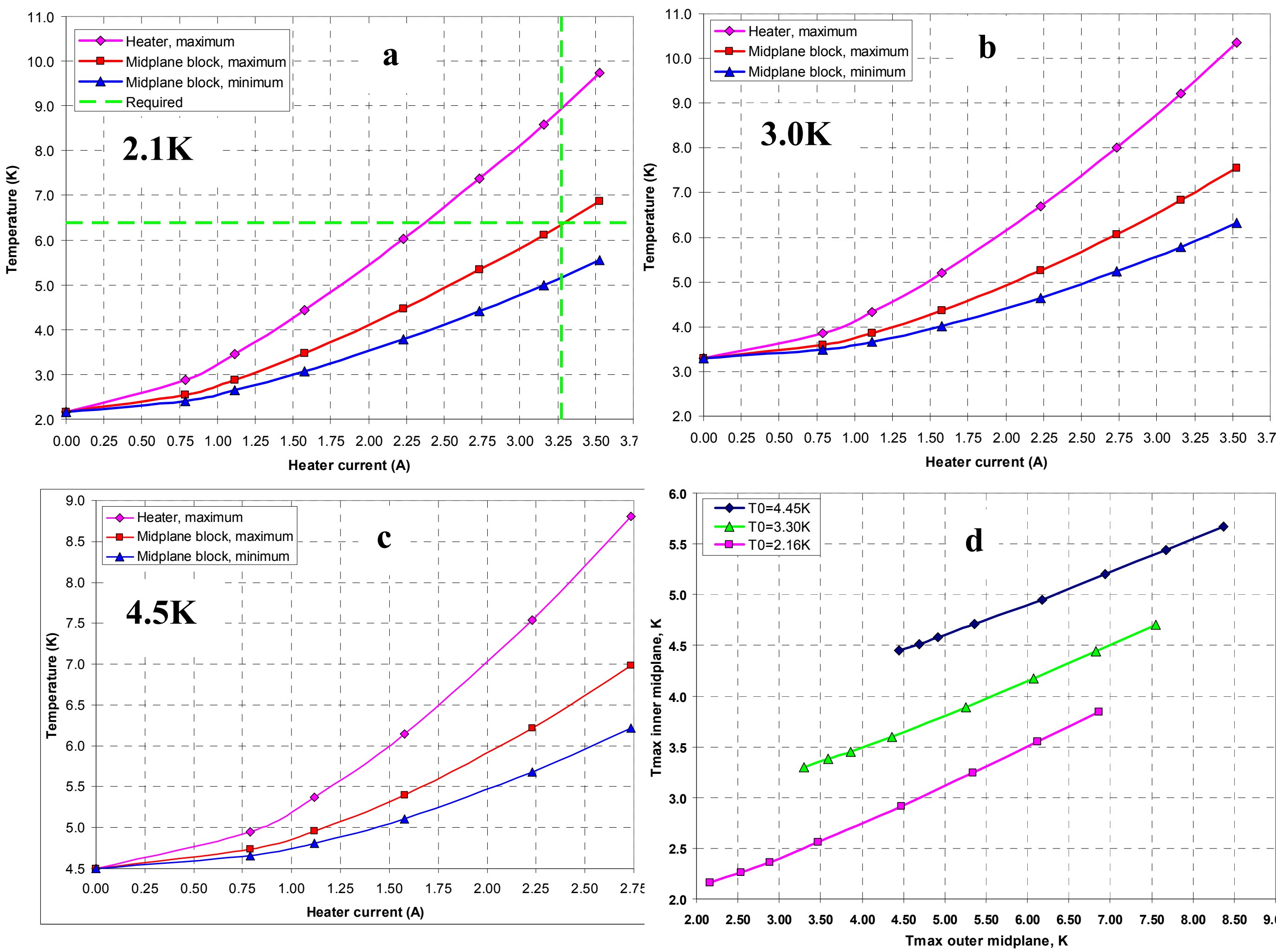


Fig.8 Temperature at the outer layer mid-plane segment as a function of the heater current simulated for 2.1 K, 3 K and 4.5 K (a , b and c). Temperature at the inner layer mid-plane segment as a function of the outer layer mid-plane segment temperature (d).

Temperatures at the outer layer mid-plane segment as functions of the heater current simulated at different helium bath temperatures are shown in Fig. 8 a, b and c. Temperature at the inner layer mid-plane segment as a function of the outer layer mid-plane segment temperature is shown in Fig. 8, d.

In the 1st thermal cycle, the test with the heater was done at 4.5 K only. The quench current as a function of the heater current for that test at 4.5 K is shown in Fig. 9. One can see that the outer layer mid-plane segment was unstable for the heater currents below ~2.4 A. The lowest heater current which still allows quenching in the inner layer segments, in fact, provides the highest quench current – because of the better performance of the inner layer at the lower temperature.

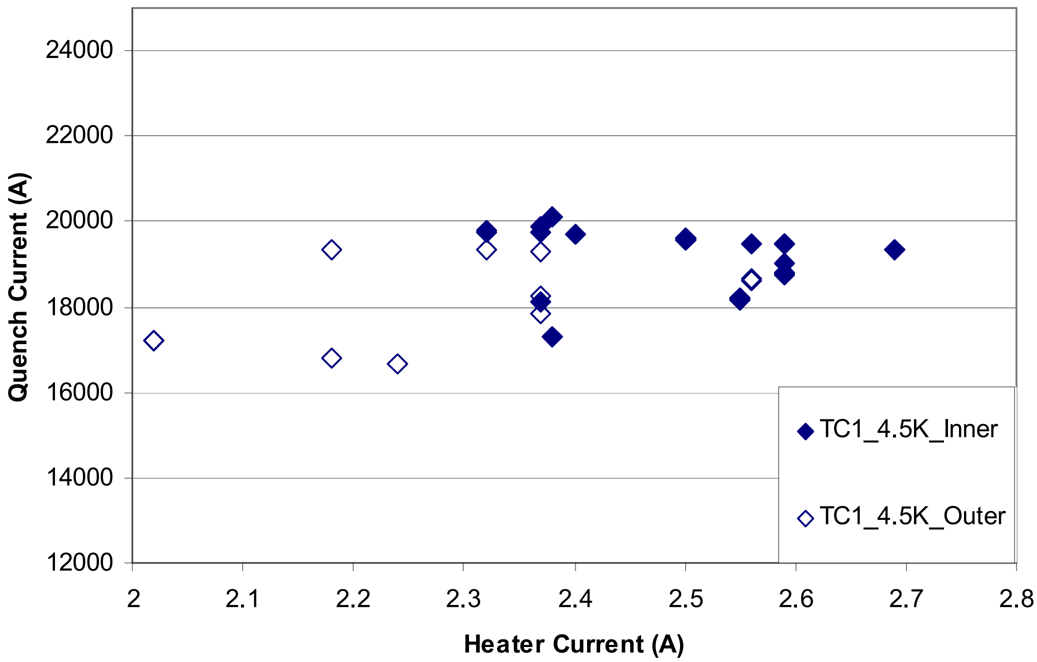


Fig.9 Quench current vs heater current for the test at 4.5 K.

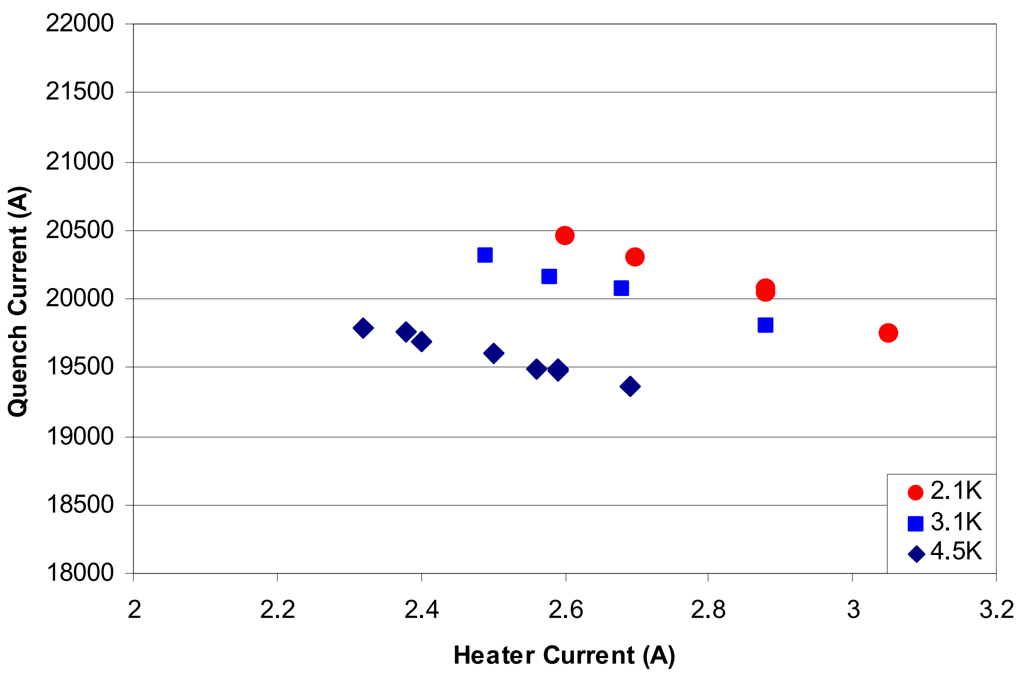


Fig.10 Quench current vs heater current for quenches in the inner layer and at 20 A/s ramp rate.

Quenches originated only from the inner layer segments for three different operation temperatures 4.5, 3.1 and 2.1 K at the 20 A/s ramp rate are shown in Fig. 10. This picture illustrates that the measurements taken at different temperatures are consistent and clearly exhibit the temperature dependence.

4. Ramp Rate Dependence

Several quenches were performed for the ramp rate dependence study at 4.5 K and 2.1 K in both thermal cycles. Summarizing plot is shown in Fig.11. Many of these quenches developed in the outer layer due to the instability problems described in Section 3. In TC-I, before we started the test with the strip heater, several conditioning ramps were performed prior to the ramp to quench. Later on more ramp rate study was done with current on the strip heater.

Ramp rate dependence for quenches in the inner layer only (i.e. with the heater current) is shown in Fig.12. One can see that quench current decreases with increasing ramp rate or temperature.

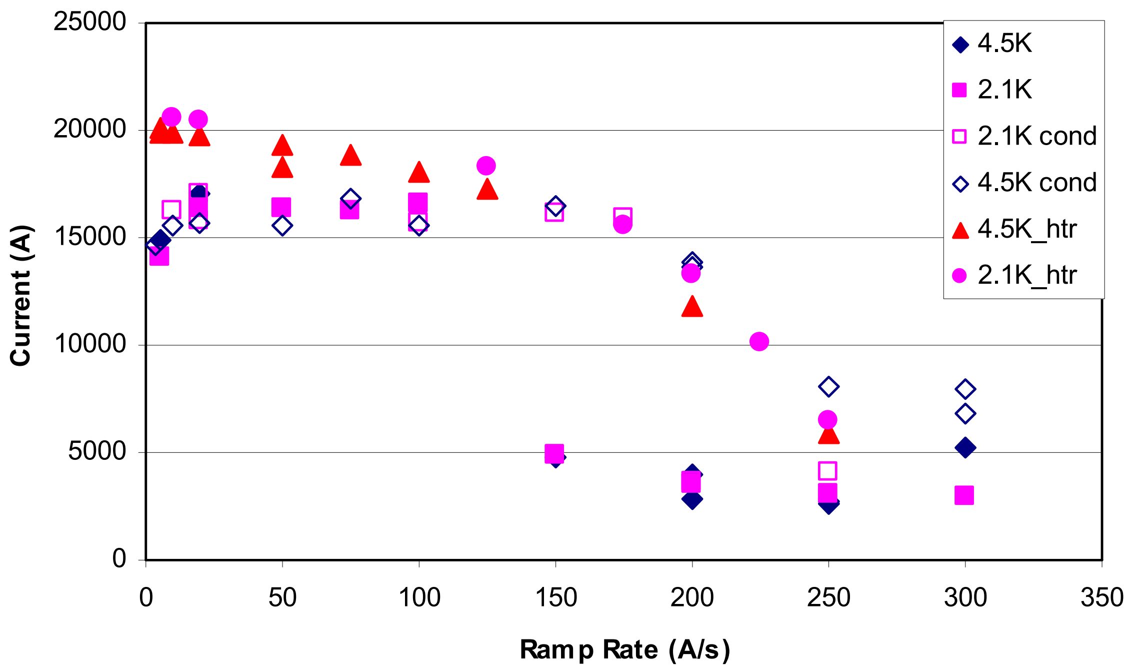


Fig.11 Ramp rate study with and without current on the strip heater.

5. Measurement of the Residual Resistance Ratio (RRR)

Estimates of RRR in LM02 coil segments have been made using data captured during the warm-up between the test cycles. The warm-up was started on December 13th and transition from superconducting to normal occurred at midnight of the same day. Due to the significant temperature gradient along the 4m-long body of the magnet the pole-turn segment at the return end still was superconductive at that time. So, data captured at 3:00 am of December 14th was used for the cold RRR measurement. Temperature of the magnet at top, middle and bottom were respectively 23.7 K, 20.5 K and 17.2 K.

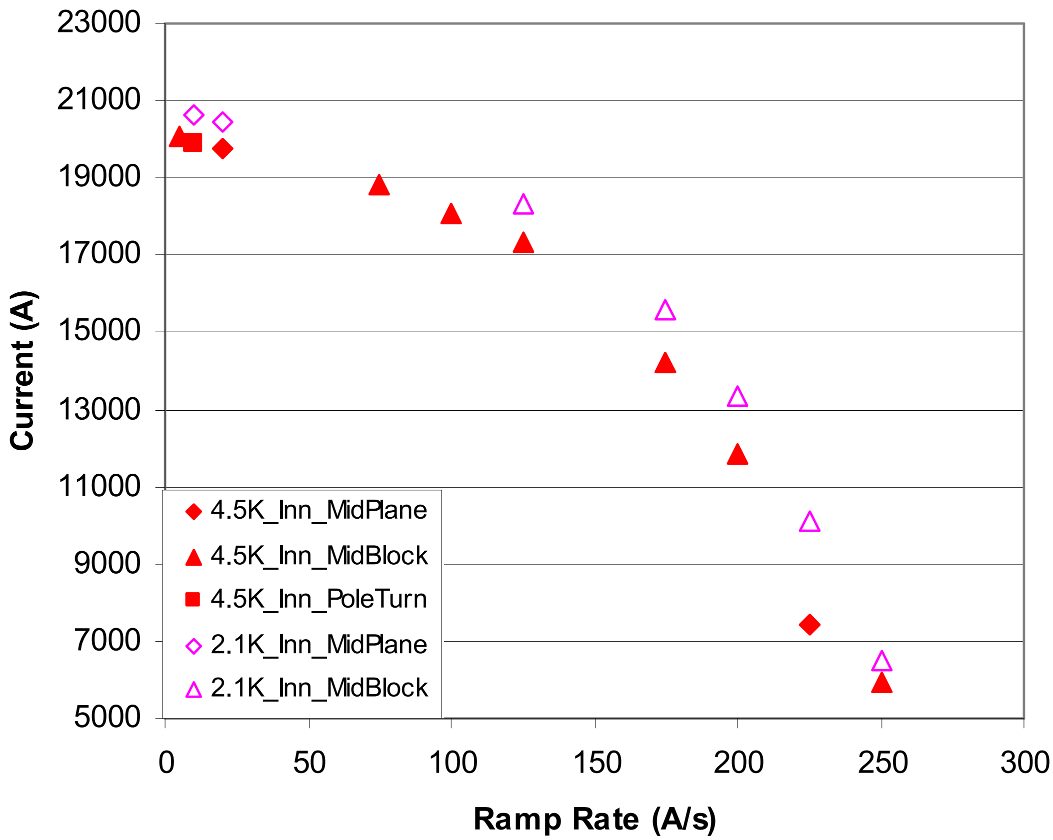


Fig.12. Ramp rate dependence for quenches in the inner layer only.

Table 3. RRR data for all segments

ΔI=I(+)-I(-) was 19.3 A for the cold and 14.5 A for the room temperature measurements

CVT segment	V(+) - V(-)	R (cold)	V(+) - V(-)	R (300K)	RRR
is30_3au	0.0044424	0.0002297	0.5122810	0.0352871	153.6
3au_8au	0.0072677	0.0003757	0.8317540	0.0572932	152.5
8au_11lel	0.0027142	0.0001403	0.3188140	0.0219606	156.5
11lel_11ler	0.0000193	0.0000010	0.0021992	0.0001515	151.8
11ler_11rer	0.0006710	0.0000347	0.0779307	0.0053681	154.7
11rer_11rel	0.0000171	0.0000009	0.0017864	0.0001230	139.1
11rel_cc	0.0006339	0.0000328	0.0729547	0.0050253	153.3
ospc_11ou	0.0028039	0.0001450	0.3260360	0.0224581	154.9
11ou_6ou	0.0067152	0.0003472	0.8238510	0.0567488	163.5
6ou_os30	0.0079133	0.0004091	1.0072700	0.0693832	169.6
Wcoil	0.0195344	0.0010099	1.5399800	0.1593510	157.8
Hcoil1 (inner layer)	0.0127205	0.0006576	0.9688430	0.1002520	152.5
Hcoil2 (outer layer)	0.0137069	0.0007086	1.1343400	0.1173770	165.6

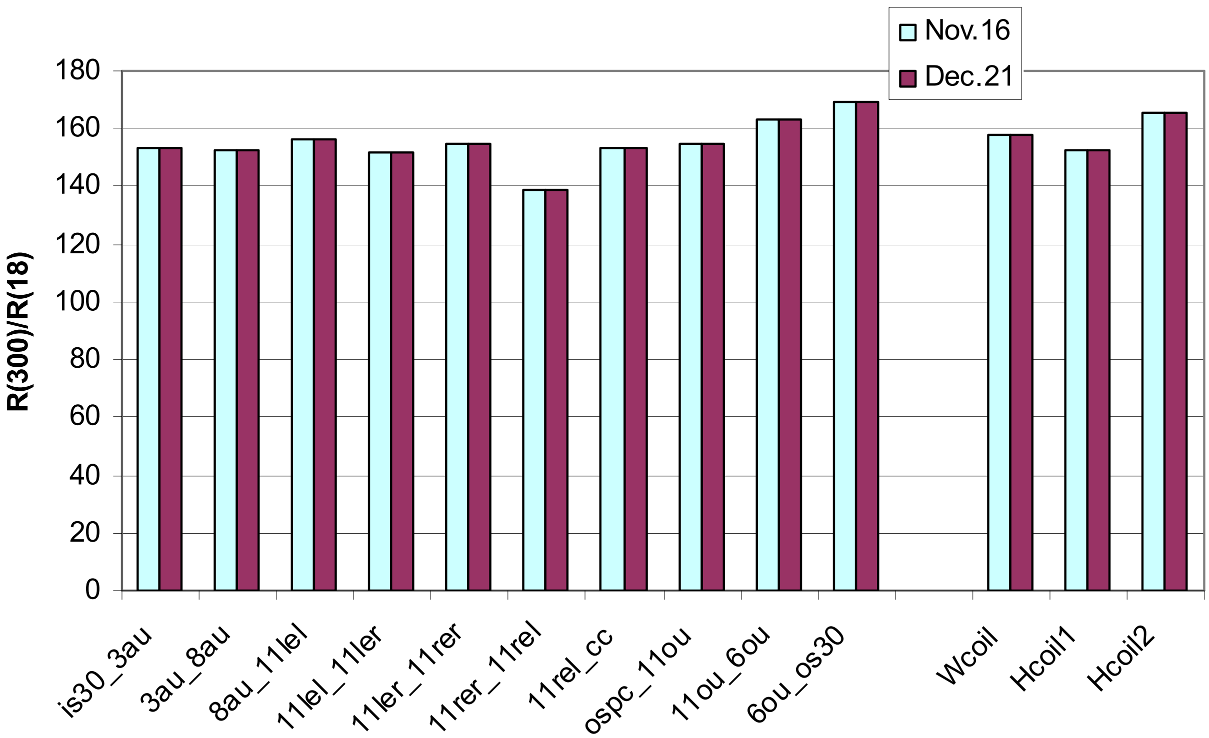


Fig.13 RRR measurements for CVT and FVT segments.

Coil voltages across "fixed" and "configurable" voltage tap segments were monitored by the *Pentek* data loggers, while a current of alternating polarity, +/- (10±0.4) A, was put through the magnet. For both warm (~ 300 K) and cold (~ 20 K) measurements we used the RRR amplifier gains for the voltage tap segments to maximize the signal levels.

The magnet reached room temperature and warm voltage measurements were captured on December 21st. Data for all segments are shown in Table 3. The results are also shown in Fig.13. For comparison we estimated RRR also for the initial room temperature measurements on November 16th.

RRR values for both the configurable and fixed voltage tap segments are reasonably consistent.

6. Quench Logic Failure

A slow ramp down occurred on November 20th when ramping up the magnet current at ramp rate of 300 A/s. The quench logic analysis showed that the ground fault AQD tripped first, followed by the half-coil signal (see Fig.14). The logic associated with a ground fault AQD trip is to disable the power supply phase-back, disable the dump fire and disable the heater fire. The heater "charge status" and "load status" never changed state for the above mentioned quench # 21, which means that the load status did not initiate the slow ramp down and the heaters did not fire. All this is consistent with the QLM logic for ground fault detection, and the logger trigger occurred at the time of the ground fault trip, which is correct.

The ground fault AQD module was tested to verify its operation and threshold setting. It was found that when a 200 mV sine wave signal was injected the positive swing had some additive noise, which increased proportional to the input signal strength. However, the noise was at the 50 mV level, which was relatively low. With the replacement AQD module installed, a 2.5 V signal was injected upstream at the ground fault resistor box to simulate a 100 mA current though the 25 Ω grounding resistor and the threshold was adjusted until the AQD tripped.

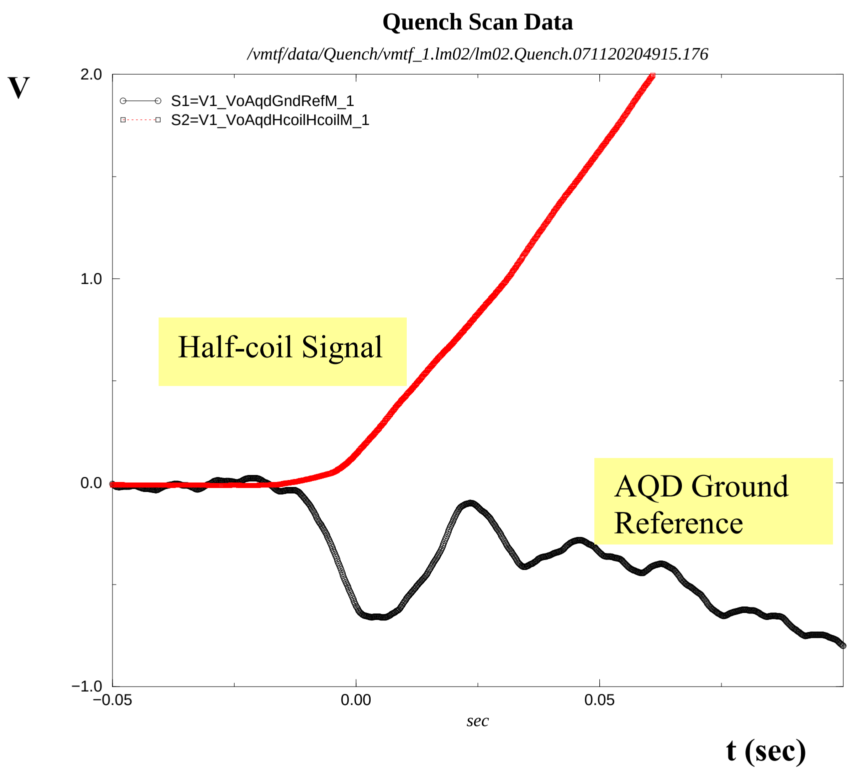


Fig.14 AQD ground reference (black) and half-coil (red) signals in quench #21.

The ground fault trip in quench #21 occurred due to a rare event in which quench was developed in both layers simultaneously. The asymmetrical grounding configuration and filter capacitor grounding scheme generated ground current from the simultaneous coil resistive growth. There was no real magnet ground fault but the ground current in this case exceeded the threshold of 100 mA before the coil quench detection thresholds were crossed resulting in a ground fault AQD trip. Since a ground fault trip initiates a slow ramp down and disables the power supply phase-back, dump fire, and heater fire, the resistive growth of the coils generated significant MIITS (~20) as a result.

It was determined that this type of event must be avoided. The near term solution was to increase the threshold of the ground fault AQD, which was increased from 100 mA to 200 mA (5 V at the input to the AQD). The long term solution is to implement symmetric grounding, which has been developed and is nearly ready to implement in VMTF. This configuration will eliminate this problem.

Nevertheless, it is still possible to get high MIITS from a symmetric quench in both half-coils (at very high ramp rates for example), and in this case we need to be able to reduce threshold on the Whole-Coil minus Idot signal.

7. Quench Locations

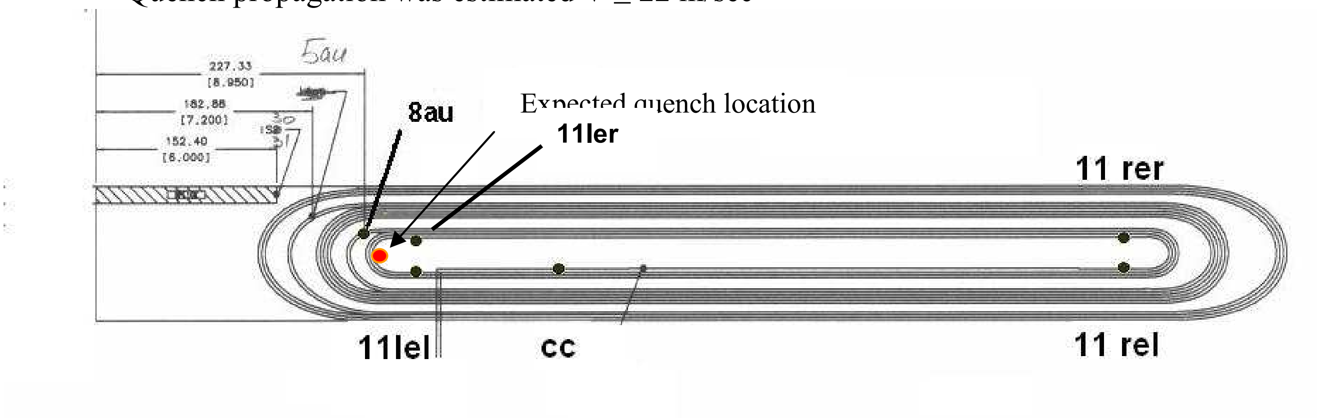
Only 8 quenches occurred in innermost segments and 7 of them in 2nd thermal cycle with the heater current. We tried to determine quench locations for these quenches using the quench onset, 1st exit and 2nd exit when available.

7.1 Quench #8, Iq=16.3kA, ramp rate 20A/s, 4.5K

First quenching segments: 11lel-11ler: -6.4 msec.

11ler-11rer: -4.2 msec.

Quench propagation was estimated $V \leq 22$ m/sec

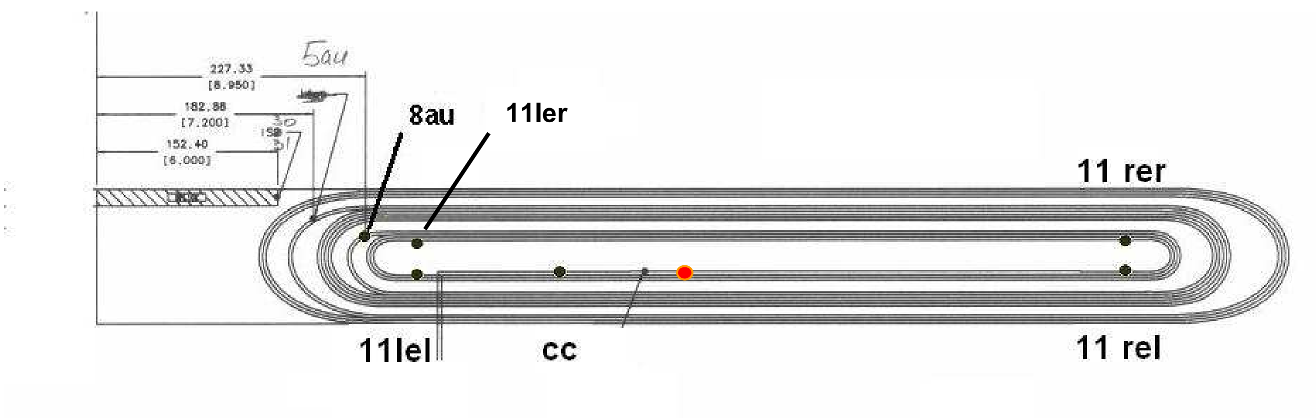


7.2 Quench #69, Iq=18.2kA, ramp rate 75A/s 4.5K

First quenching segments:

8au-11lel: -3.2 msec. 11lel-11ler: -2.8 msec.

11rel-cc: -3.2 msec. 11rer-11rel: -2.8 msec. 11ler-11rer: -2.4 msec.

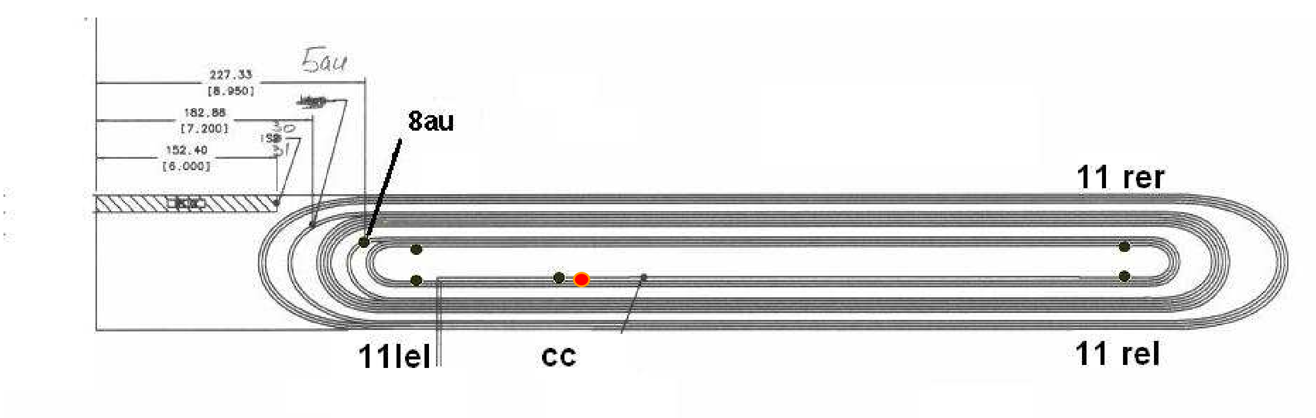


7.3 Quench #96, Iq=18.2kA, 4.5K, 10A/s

First quenching segments: 11rel-cc: -3.7 msec.

8au-11lel: -3.3 msec.

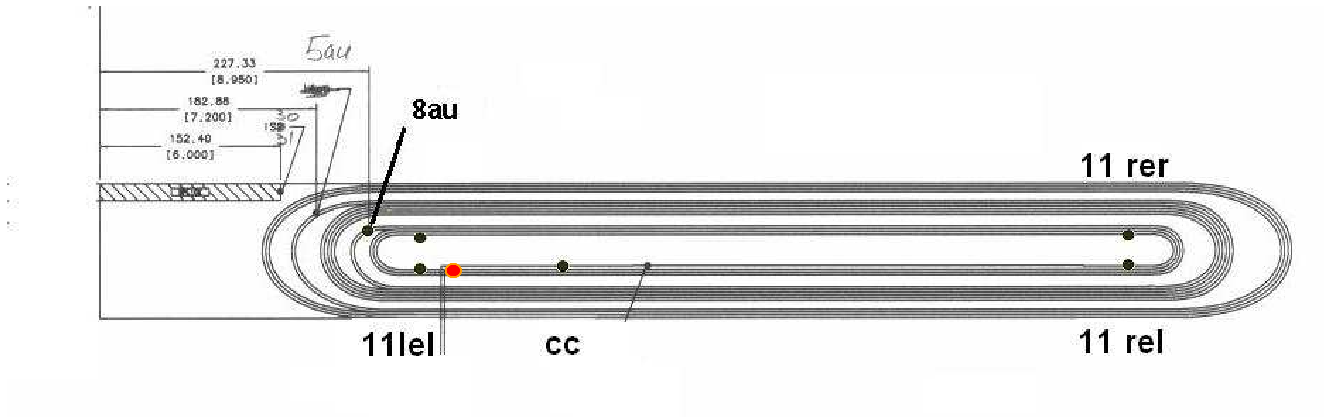
11lel-11ler: -2.7 msec.



7.4 Quench #108, Iq=18.9kA, 4.5K, 20A/s

First quenching segments:

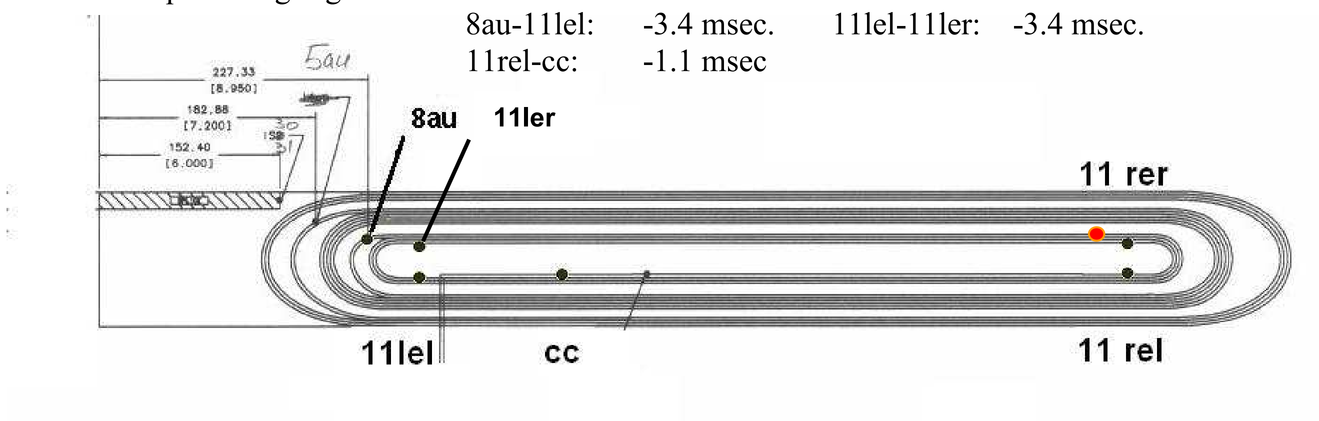
8au-11lel: -4.4 msec.
cc-11ou: -4.4 msec. (recovering)
11lel-11ler: -3.7 msec.
11rel-cc: -2.1 msec.



7.5 Quench #109, Iq=19.2kA, 4.5K, 20A/s

Firstquenching segments:

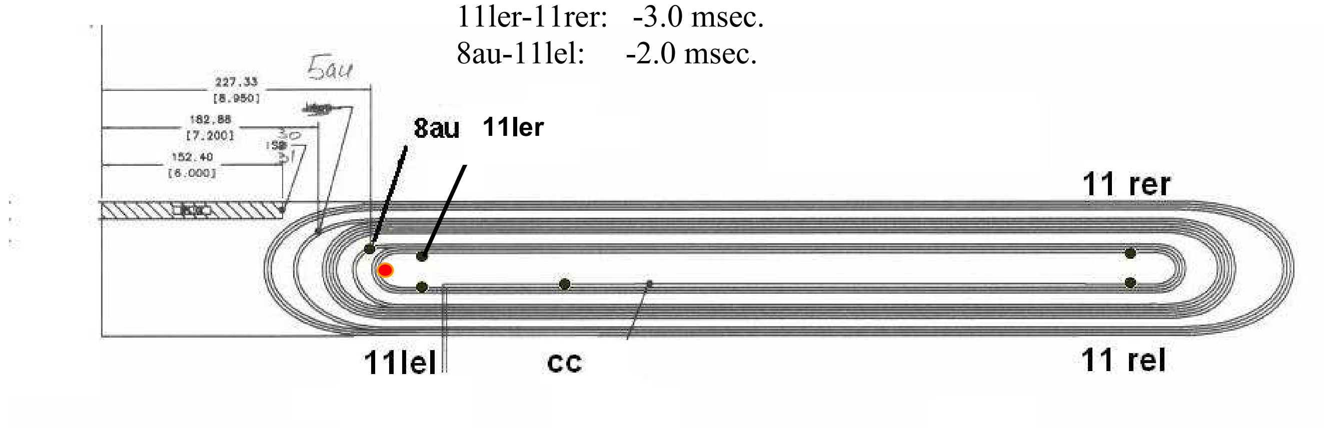
11ler-11rer: -3.6 msec.
8au-11lel: -3.4 msec.
11rel-cc: -1.1 msec
11rer-11rel: -3.6 msec.
11lel-11ler: -3.4 msec.



7.6 Quench #111, Iq=19.5kA, 4.5K, 20A/s

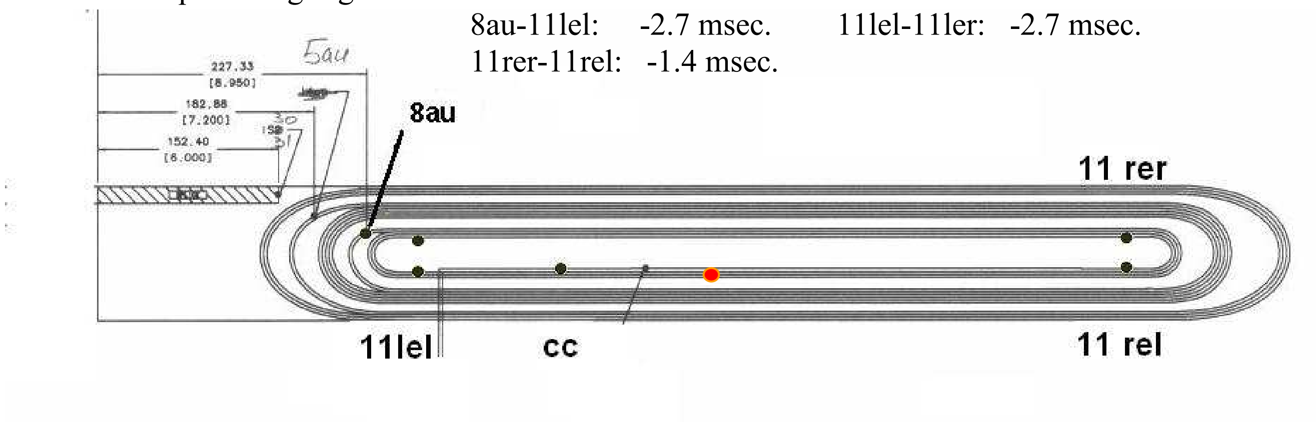
First quenching segments:

11lel-11ler: -3.7 msec.
11ler-11rer: -3.0 msec.
8au-11lel: -2.0 msec.



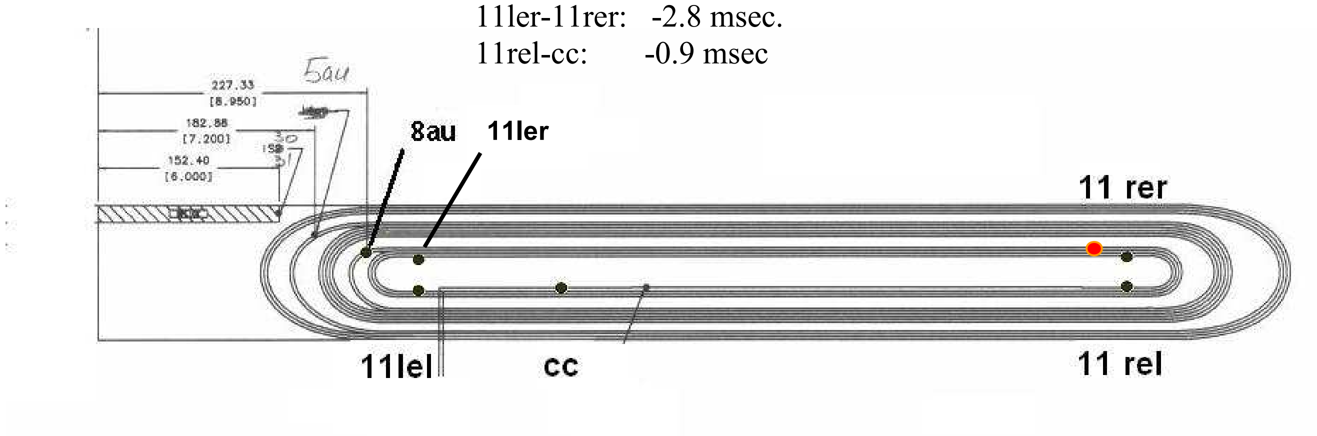
7.7 Quench #117, Iq=19.9kA, 2.16K, 20A/s

First quenching segments: 11rel-cc: -4.4 msec.
8au-11lel: -2.7 msec. 11lel-11ler: -2.7 msec.
11rer-11rel: -1.4 msec.



7.8 Quench #121, Iq=20.2kA, 2.16K, 20A/s

First quenching segments: 11rer-11rel: -3.6 msec.
8au-11lel: -2.8 msec. 11lel-11ler: -2.8 msec.
11ler-11rer: -2.8 msec.
11rel-cc: -0.9 msec



8. Conclusion

LM02 magnet was fabricated as a part of the Nb_3Sn accelerator magnet technology scale-up program at Fermilab. The 4-m long coil of this magnet was made of 1-mm Nb_3Sn strands based on the "Restack Rod Process" (RRP) of 108/127 sub-element design. Previously, small racetrack magnet SR03 [2] and 1-m long mirror magnet HFDM06 [3] were built at Fermilab using nominally same conductor, but these magnets showed better quench performance.

Cable for the LM02 coils was made using 3 different billets 8195 (8 strands out of 27), 8197 (3) and 9272 (16), while cable for SR03 and HFDM06 magnets was made of strands from the first two billets only. Another factor that was different between these magnets is that SR03 and HFDM06 coils were reacted in a short oven, while LM02 coil was reacted in the long oven at Fermilab – the reaction mold was then found to be bowed, although mechanical analysis suggests this should not have introduced sufficient strain to be a concern. Also, preload achieved after LM02 assembly was greater than for HFDM06. Another 1-m coil from the same LM02 cable was reacted in the long oven prior to LM02 coil, and was to have been tested in the HFDM07 mirror configuration; however it has not yet been collared and remains available for possible assembly and testing to eliminate some variables to narrow the possibilities in explaining LM02 performance.

Low field instability was found responsible for the initial erratic quench current limitation in the outer layer mid-plane segment of the LM02 magnet. Significant improvement in quench current was achieved after the conductor was locally warmed-up in the above mentioned region using the strip heater. Quench location also moved from the outer to the inner layer of the magnet, mostly to the mid-plane segment of the inner layer, and exhibited some training.

Current on the strip heater was varied in 2-3 A region. Expected short sample limit weighted by actual billet distribution in LM02 cable, was estimated as 23.7 kA for the highest field region in the magnet at 4.5K. Maximum quench current 20.7 kA was reached with the heater current 2.4 A (i.e. with worse temperature conditions) and for the inner layer mid-plane segment (not highest field region) at 4.5 K.

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2. S.Feher et all., "SR03 Test Summary Report", TD-06-047, 2006

3. M.Tartaglia et all., "HFDM06 Test Summary Report", TD-07-016, 2007